Influence of DEM resolution on surface flow network for pluvial urban flooding and simulations of integrated system

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ABSTRACT

This paper presents the developments towards the next generation of overland flow modelling for analysis of urban pluvial flooding. The input data for the surface drainage network are generated automatically using detailed analysis of Digital Elevation Model (DEM). Developed tools for input data generation allows the user to define the surface flow network consisting of pathways and temporary ponds (flooded areas) and to link it with underground network through inlets. In this paper the emphasis is placed on detailed sensitivity analysis of ponds and the preferential pathways creation. Four DEM data sets for the same catchment were considered in order to compare the results obtained using the methodology. The DEMs used were generated from different acquisition techniques; hence have different resolutions and accuracy. The results obtained by the applied methodology show that they can represent the surface flow network reliably but differences need to be analysed separately. Comparing the results obtained by different data sets, the quality of the surface network generated is highly dependent on the quality and resolution of the terrain data sets. Relevant conclusions are drawn.

KEYWORDS

Digital Elevation Model; Dual drainage; Flood modelling; Overland flow; Urban drainage.

INTRODUCTION

Urban flooding is currently one of the major and costly environmental hazards. According to DEFRA (2008) UK Environmental Agency assessed that two-thirds of the 57,000 homes affected in June and July 2007 in UK were flooded from surface water runoff overloading drainage systems causing damage of over £3 billon. In order to minimise the risk of flood events, taking the current "industrial standards" into account, significant improvement in modelling for analysis and prediction and quantification of the flood is needed. This is especially the case for the over-ground component of the process. Urban flooding may be caused by a number of factors but the primary reason is the limited capacity of the sewer systems which results, during extreme storms, in water being discharged to the catchment surface through the manholes or sewer inlets. The overland flow subsequently travels across the surface along the flood pathways. Such flow pathways can transfer flow over significant distances so that flood events may occur at remote locations when compared to the place where the drainage system capacity is exceeded. Surface runoff from adjacent areas that are not directly connected to the drainage system can also contribute to flood flow. Consequently, urban drainage modelling requires a detailed representation of the above process which is dominated by terrain features in order to represent ponds and flow pathways, i.e. to reliably analyse flooding dynamics and the volume conveyed in the surface.

The emerging of high-resolution Digital Elevation Models (DEM) technology, such as LiDAR and their availability at affordable cost, makes a detailed analysis of overland flow feasible. The potential for further development opens new possibilities to enhance the capability of the next generation of urban flood models as suggested by Maksimović and Prodanović (2001), beyond the limitations reported by Mark *et al.* (2004).

The approach presented in the paper by Boonya-aroonnet *et al.* (2007) in modelling overland flow in urban environments, caused by extreme rainfall, was originally investigated by Prodanović (1999) and Djordjević (2001). The concept is based on a GIS-centred analysis of DEM data set. The essential features to identify flood vulnerable areas (mainly ponds) are derived, and the geometric characteristics of the preferential flow pathways are computed. This representation of overland flow can then be modelled by decentralised, physically based approach and may then be coupled with a sub-surface (sewer) network model by applying a physically based modelling concept, developed by Maksimović and Radojković (1986). Hence, the tool developed identifies the surface depressions and flow pathways, and generates all links and interactions with the underground sewer network. The results produced are then coupled with urban drainage hydraulic models. Currently, the tool is fully compatible with the SIPSON model (Djordjević *et al.*, 2005) and with other standard commercial hydraulic models, such as InfoWorks (Wallingford Software, 2008).

This paper presents a comparison of the surface flow networks generated from four data sets that cover two small urban neighbouring catchments in Lisbon (Portugal). The total area of both catchments is 0.8km^2. The northern part of the catchments consists mainly of crop fields and just a few buildings, and may be considered non-urban. The lower, downstream part of catchment is highly urbanised with a high percentage of imperviousness. The catchments are representative for such tests since they have different slopes: an almost flat area near the south border of the catchment, and a relatively steep area in the Northern part.

DEM FOR MODELLING PLUVIAL URBAN FLOODING

There are several techniques available to represent terrain. The selection of a specific technique will rely on the accuracy needed, the extent of the area of interest, budget, time frame, etc (Smith *et al.*, 2006). Additionally, each area has its own characteristics that may suit best one technique in favour of others. In this study, four DEM generated by different techniques were considered (compared) in order to generate and analyse the surface flow network. The following four DEM techniques were used: InSAR (SRTM elevation data), Cartographic based elevation data (contour DEM), original LiDAR data and LiDAR with superimposed buildings.

The “imperfections” in DEM will directly deteriorate the result of the surface network delineation model, so it is of utmost importance to have a DEM with as little noise and errors as possible. Since quality of DEM mostly depends on the source of data, a detailed DEM analysis and pre-processing is required. The best approach would be to produce a custom tailored DEM with a pre-specified resolution (Garbrecht and Martz, 2000). However, in the majority of the cases this solution is cost prohibitive, and a DEM data set already available is used. Therefore, the usual procedure is to get a better DEM is to correct or replace the existing one.

Assuming that small corrections of the DEM are needed to guarantee that flow pathways algorithms run without problems, changes (depression filling and artificial sloping of flat terrain) and smoothing techniques should be kept to a minimum. Other potential methods to solve these problems were presented by Band (1986), Garbrecht and Martz (1996), Jenson and Domingue (1988), Martz and De Jong (1988), Martz and Garbrecht (1995), O'Callaghan and Mark (1984) and Prodanović (1999). However, there is no standard way to smooth the DEM. Techniques used include frequency analysis of DEM data and low-pass filtering, but there is scope to enhance these techniques (Leitão *et al.*, 2006).

IMPLEMENTATION

The area chosen to perform the tests represents two neighbouring catchments of about 0.8km^2 in Lisbon, Portugal. The four data sets chosen in order to compare the results obtained using the developed tool cover an area of approximately 3km^2, and were acquired using different acquisition techniques hence have different characteristics, as described below.

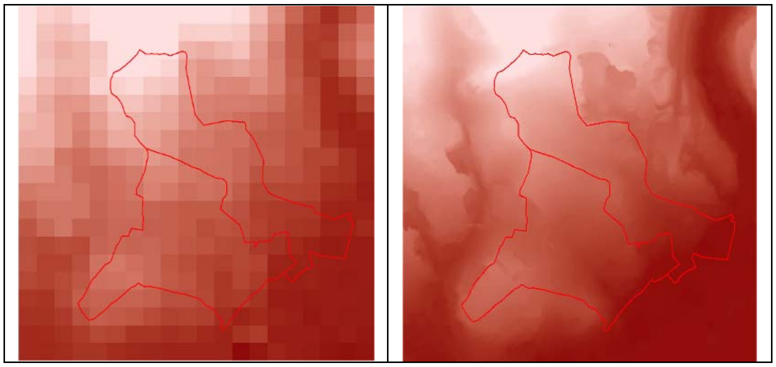
The data set with the lowest resolution considered was the SRTM 90m DEM. It was downloaded from the SRTM website (Jarvis *et al.* 2006) for the area of interest. As described in the literature, horizontal resolution is 90m in the equator, and vertical accuracy is up to 16m. After having been cropped, the SRTM DEM has 20 rows and 20 columns.

The second DEM, obtained by the cartographic technique was generated by digitising the contour lines of a topographic map. The map's contour interval was 5m. This DEM represents bare earth; however there are some artefacts (roads, railways, rivers) that may be represented as well, as presented in Figure 6. The number of rows and columns is 360, and the cell size is 5m.

The highest resolution DEM available for this test was generated using the LiDAR technique. It was provided by Edinfor - Portugal, and has a documented vertical accuracy of 0.15m and a horizontal accuracy of 0.5m. For the selected area the data set has 1800 columns and 1800 rows with a cell size of 1x1m. This DEM was generated from the LiDAR Digital Surface Model (DSM) using stripping methods in order to remove the vegetation and buildings.

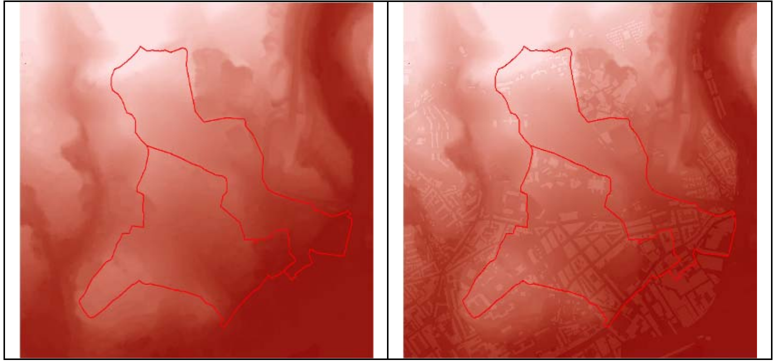
The fourth terrain elevation model (LiDAR$_b$ DEM) is based on the above LiDAR DEM. In this case, the building's elevation was added to the LiDAR DEM. Although a fixed elevation (10m) was considered in order to represent buildings it was enough to create correct slopes in the DEM and prevent water paths to cross the buildings. In Figure 1 the DEMs obtained by the above four methods are presented. Higher elevation is represented in light colours. The maximum elevation is about 140masl and the minimum elevation 2masl.

The following files, along with the DEM, are required to generate the surface network: (i) manholes, (ii) buildings, (iii) aspect file, and (iv) catchment's boundary.



(a) SRTM DEM (cell size 90x90m).

(b) contour DEM (cell size 5x5m)



(c) LiDAR DEM (cell size 1x1m)

(d) LiDAR_b DEM (cell size 1x1m)

Figure 1. DEMs used in the case study (Lisbon).

RESULTS

To assess the influence of DEM's vertical accuracy and spatial resolution on generation of the surface network, the algorithm was applied to all DEMs. Results of the number of ponds delineated and pathways obtained by the four different DEM are compared. The pond filtering algorithm is also tested for the four DEM. Flow pathways generation results are compared between the four used data sets. The number of pathways generated and the number of erroneous flow pathways are evaluated. At the end, a more detailed comparison between the LiDAR DEM and the LiDAR_b DEM is performed in order to assess the influence of the representation of buildings in the DEM when the surface flow network is to be generated.

Ponds

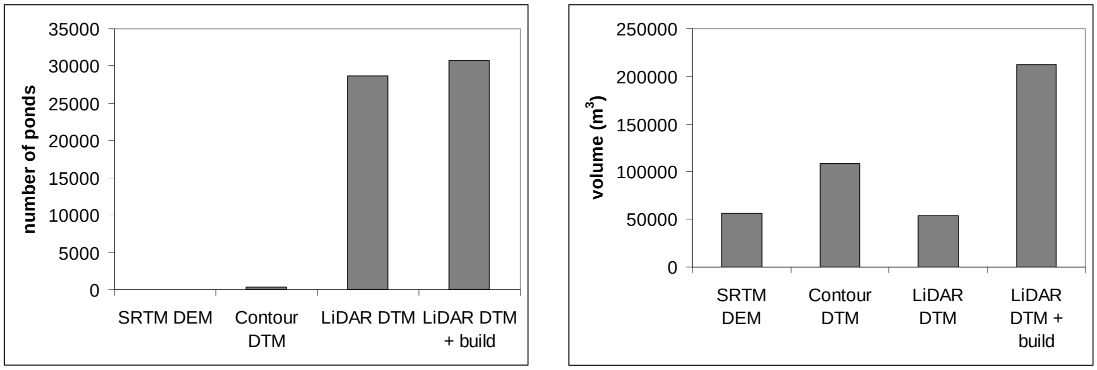
The first step to generate the surface network is to identify the surface storage locations. These locations, called ponds, are natural or man-made depressions in the terrain that store water during and after a rainfall event. They have an enormous importance in the rainfall-runoff process because they can store a big amount of water, not flowing over the surface. They play also an important role in the flood prediction, as their locations are potential flood risk areas. The numbers of ponds delineated are significantly different between the DEM used, as presented in Table 1.

The SRTM DEM produced a very small number of ponds due to its very low resolution. In the case of the contour DEM, 386 ponds are identified while with the LiDAR data sets the number of ponds identified is very close to 30,000, in both cases. Although, the huge difference in terms of number of ponds between the contour and LiDAR DEM, the area occupied by ponds in both cases is similar. However, the storage capacity calculated by contour DEM is twice bigger when compared with the LiDAR DEM.

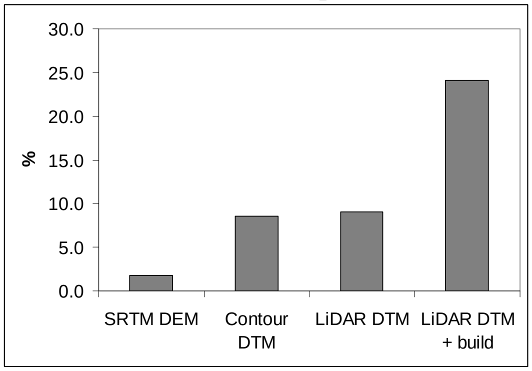
Table 1. Comparison of the pond delineation results obtained by the four applied methods.

DTM no.	Name	Number of ponds	Area occupied by ponds (m^2)	% of catchment area occupied by ponds	Ponds storage capacity (m^3)
1	SRTM DEM	3	56,700	1.75	56,700
2	Contour DEM	386	277,550	8.57	108,622
3	LiDAR DEM	28,630	292,758	9.04	53,652
4	LiDAR$_b$ DEM	30,702	780,726	24.10	212,348

When LiDAR DEM and LiDAR$_b$ DEM are compared, there is a small difference in number of ponds, but huge differences in terms of area occupied by ponds and storage capacity. The results present in Table 1 are graphically shown in Figure 2.



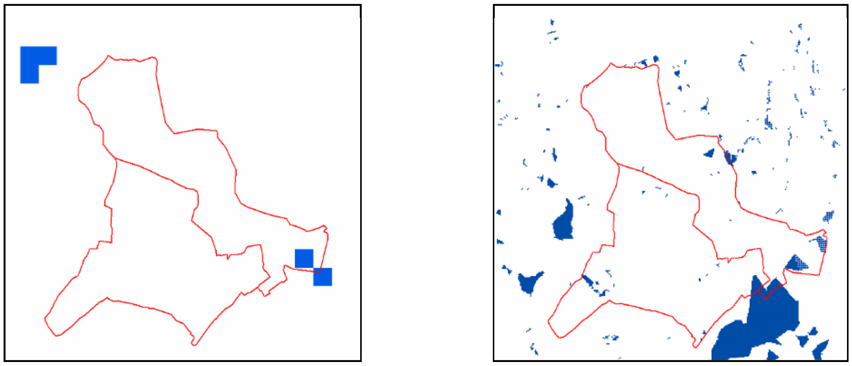
(a) number of ponds (b) Ponds storage



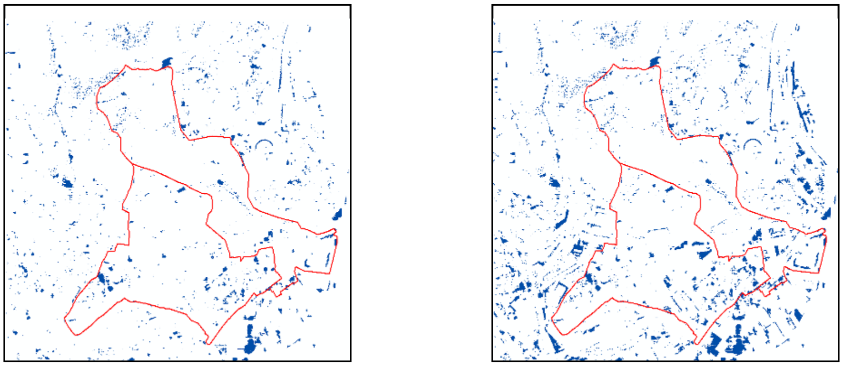
(c) % of catchment occupied by ponds

Figure 2. Comparison of the pond delineation results obtained using four different DEM.

In Figure 3 the location and dimension of the delineated ponds are presented for each of the DEMs. One can see the locations of the ponds and their overall size as well.



(a) SRTM DEM (b) contour DEM



(c) LiDAR DEM (d) LiDAR_b DEM

Figure 3. The result (maps) of pond delineation for the four elevation model data sets.

Ponds filtering

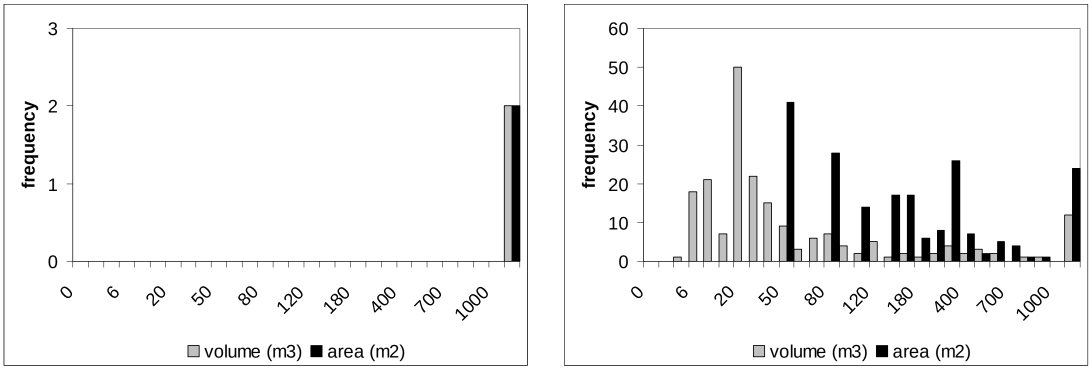
As can be seen in Figure 3, the analysis of the size of ponds reveals that there are many small ponds that could be deleted without significant loss of essential information. The ponds generated using the four DEM were filtered out using the same criteria. Ponds with less than 0.2m depth and less than $5m^3$ are discarded. The number of ponds removed and storage lost are presented in Table 2.

Table 2. Pond filtering results.

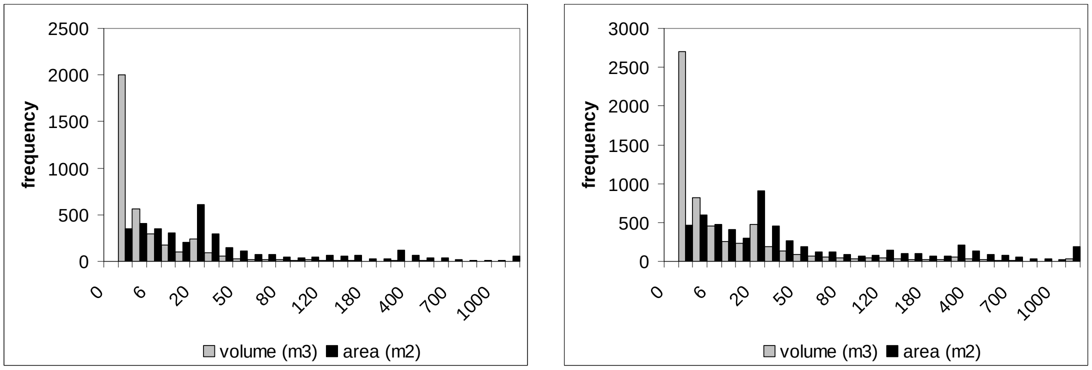
DEM no.	Name	Number ponds removed	% of ponds removed	Storage volume lost (m^3)	% storage lost
1	SRTM DEM	1	33.3	16,200	28.57
2	Contour DEM	185	47.9	4,925	4.54
3	LiDAR DEM	24,963	87.2	21,642	40.34
4	LiDAR_b DEM	24,817	80.8	13,435	6.33

The percentage of ponds removal varies between 47.9% for the contour DEM case to 87.2% for the LiDAR DEM by applying the same criteria, excluding the SRTM result. It is difficult to link the number of ponds removed to the storage volume lost by applying the filtering algorithm because in the case of the LiDAR_b DEM the percentage of ponds removed is very close to the percentage of ponds removed in the LiDAR DEM case but the storage volume lost is significantly different. This situation can be explained by much bigger storage volume calculated with the LiDAR$_b$ DEM mainly due to the ponds enclosed by buildings. Figure 4 shows the area and volume pond's distribution after performing the pond's filtering procedure.

Again, the SRTM results are not to be considered since they cannot be related to the reality. For the other three cases it can be seen that all ponds with less than 5m^3 were removed. It is also interesting to see how different is the distribution of ponds between the contour DEM and LiDAR DEM and LiDAR$_b$ DEM. In the first case there is not a big number of small ponds with small volume. Instead, the number of ponds is similar over a large range of area and volume values. For the case of the LiDAR elevation models there is a huge number of small ponds. This fact is in agreement with the higher resolution (small cell size) presented in these cases.



(a) SRTM DEM (b) Contour DEM



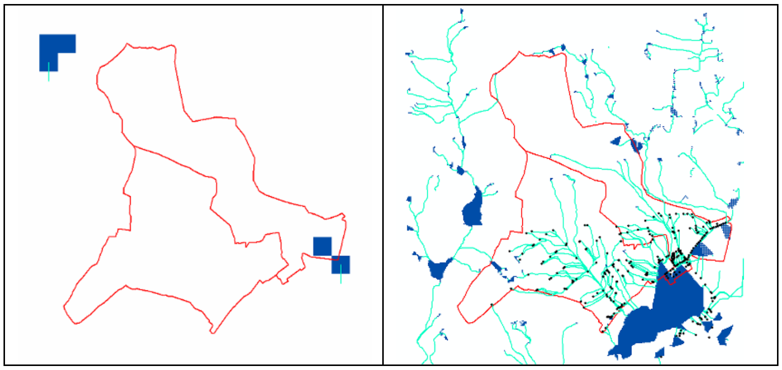
(c) LiDAR DEM (e) LiDAR$_b$ DEM

Figure 4. Ponds area and volume distribution for the four tested DEM/DEM data sets.

Flow pathways

The flow pathways were also generated for the above four elevation models, using the "rolling ball" technique implemented by Prodanović (1999). Flow pathways start on every delineated pond and manhole, and flow along the surface until a termination criterion is reached (end of image, manhole or other pond). Figure 5 presents the results of the pathways generation. As it can be seen in Figure 5 the results obtained using the contour and LiDAR DEMs show satisfactory results. In these three cases, Figure 5 (b, c and d), the flow pathways starting at the ponds and at the manholes are visible.

In Figure 5 (c and d) the surface flow network is very dense. This is due to the big number of small ponds delineated in the previous pond delineation step. In order to build and run the hydraulic model, number of ponds on these two cases must be reduced even more using bigger values for the pond filtering parameters. Other tests have been made in order to compare these results with the "natural" flow pathways usually generated using the flow accumulation image and commonly used in rural catchments. A threshold has to be defined with this method that depends on the terrain characteristics (slope) and also on the DEM resolution. Tarboton *et al.* (1991) and Prodanović (1999) presented methodologies to define this threshold value. However, for urban catchments, no definitive methodology is yet established and further work is needed which is been carried at the Urban Water Research Group (Imperial College London). The number of pathways generated shows a considerable increase from the contour DEM to the LiDAR elevation models (see Figure 6).


(a) SRTM DEM (b) contour DEM

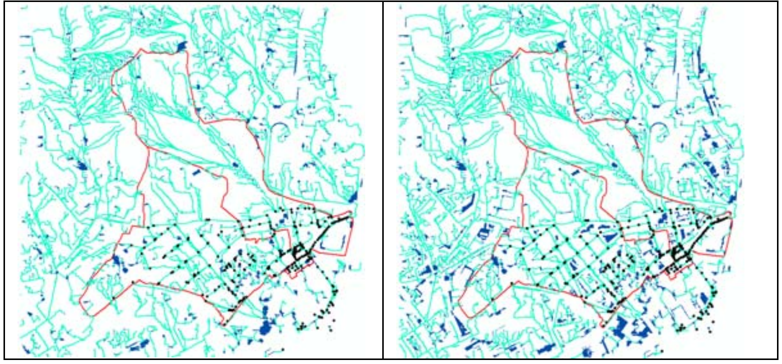

(c) LiDAR DEM (d) $\mathrm{LiDAR_b}$ DEM

Figure 5. Flow pathways delineation results maps.

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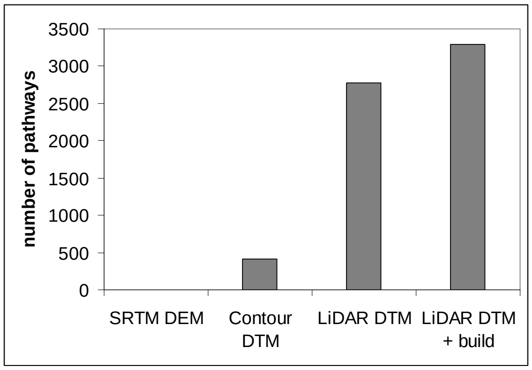

Figure 6. Results of flow pathways delineation – number of pathways.

Comparison between LiDAR DEM and LiDAR$_b$ DEM

Different results were obtained using the LiDAR and LiDAR$_b$ data sets. They were presented in the previous sections and a detailed picture is presented in Figure 7. As shown, a few issues presented in the results generated by the LiDAR DEM are solved, namely, ponds inside buildings and pathways crossing buildings. As can also be seen by the comparison of Figure 7(a) and 7(b), an extra set of ponds is delineated in the case of LiDAR$_b$ DEM. These extra ponds are mainly located near building walls. In these cases, buildings act as barriers to the flow, increasing the number of ponds identified in the DEM and increasing the depth of existing ponds without considering buildings at the same time. These probably are the reasons for the massive increase in pond storage capacity in this latter case when compared with the results obtained using the LiDAR DEM.

(a) LiDAR DEM (b) LiDAR$_b$ DEM

Figure 7. Buildings influence on ponds delineation procedure.

USE OF THE DELINEATION OF SURFACE FLOW NETWORK IN URBAN DRAINAGE MODELLING

The results of the surface flow network delineation are to be introduced into an urban drainage model. The model will then be able to simulate the interactions of the buried sewer system and the surface flow network (ponds and pathways). A few simulations have already been conducted using the surface network generated by developed tool. Leandro *et al.* (2007) studied the interactions between the surface and underground models, coupling the two systems using the SIPSON model (Djordjević *et al.*, 2005), and Ho and Maksimović (2006) performed simple simulations in order to identify the Capabilities and Limits of Urban Pluvial Flood Modelling using InfoWorks CS.

CONCLUSIONS

A new concept for the generation of the surface flow network (ponds and pathways) based on the Digital Elevation Models is presented in the paper. Four DEM were used to compare the results obtained by the delineation methodology. The DEMs used were generated from different acquisition techniques; hence have different resolution and accuracy.

As a conclusion it can be stated that the results obtained by the applied methodology represent the surface flow network reliably if a high resolution (LiDAR) data set is used. Comparing the results obtained using four different elevation models, it can be concluded that the quality of the surface network generated is highly dependent on the resolution and accuracy of the elevation data set used. The results obtained with the SRTM DEM are far from a good description of the "real" surface flow network. The resolution of this data set is so low that sewer manholes cannot be represented and accounted for surface network generation.

Representation of buildings was found to be important. A great increase in the area occupied by ponds is noticed when the results obtained using the two LiDAR data sets are compared. This may be due to the fact that building act as barriers to the flow, creating new ponds and/or increasing their depth/area. Thus the realistic representation of buildings is essential for improved generation and analysis of the surface flow network.

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