Enhanced DEM-based flow path delineation methods for urban flood modelling

J. P. Leitão, D. Prodanović, S. Boonya-aroonnet and Č. Maksimović

ABSTRACT

In order to simulate surface runoff and flooding, one-dimensional (1D) overland flow networks can be automatically delineated using digital elevation models (DEM). The resulting network comprises flow paths and terrain depressions/ponds and is essential to reliably model pluvial (surface) flooding events in urban areas by so-called 1D/1D models. Conventional automatic DEM-based flow path delineation methods have problems in producing realistic overland flow paths when detailed high-resolution DEMs of urban areas are used. The aim of this paper is to present the results of research and development of three enhanced DEM-based overland flow path delineation methods; these methods are triggered when the conventional flow path delineation process stops due to a flow obstacle. Two of the methods, the 'bouncing ball and buildings' and 'bouncing ball and A*' methods, are based on the conventional 'bouncing ball' concept; the third proposed method, the 'sliding ball' method, is based on the physical water accumulation concept. These enhanced methods were tested and their results were compared with results obtained using two conventional flow path delineation methods using a semi-synthetic test DEM. The results showed significant improvements in terms of the reliability of the delineated overland flow paths when using these enhanced methods.

Key words | digital elevation models, dual-drainage modelling, overland flow path delineation, pluvial flooding, urban water

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INTRODUCTION

Flood events caused by intense rainfall, which are becoming considerably more frequent, can cause significant damage, especially in urban areas. According to Pitt (2008), over 60% of flooding damage in urban areas in the UK in 2007 flood events was caused by this type of flood. Enhanced urban drainage models are therefore needed to simulate correctly the hydraulic behaviour of the drainage systems and accurately predict flood location, magnitude and duration. These models are important tools for city planners, drainage utility managers, emergency managers and other decision makers.

Until recently, conventional urban drainage models only considered the flow in the sewer system, neglecting the impacts of the overland flow system and the links between these two systems in cases of urban flooding. However, to accurately model the drainage system during flooding events it is necessary to include both the sewer and the overland flow systems, in other words, to implement the dual-drainage concept, as described by Djordjević *et al.* (1999). This concept relies on the simultaneous simulation of both sewer and overland flow systems that are connected through the computational nodes (manholes). Kinouchi *et al.* (1995) and Mark *et al.* (2004) investigated the numerical problems associated with the simultaneous modelling of the two linked systems using a simple concept, in which the overland flow route is parallel to the (underground) sewer system. In these two studies, the overland flow system corresponded to the roads of the catchment. Some commercial software packages, e.g. Infoworks CS (Innovyze 2011), have tools to automatically generate overland flow paths based on digital elevation models (DEM). However, these tools are not capable of generating full overland flow systems, as

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they do not identify terrain depressions, i.e. flood-prone areas.

Several works (Boonya-aroonnet *et al.* 2007; Adeyemo *et al.* 2008; Leitão *et al.* 2009) have shown that the methodology developed by Maksimović *et al.* (2009), called AOFD (Automatic Overland Flow Delineation), and tested by Allitt *et al.* (2009), offers a consistent way of automatically producing one-dimensional (1D) overland flow networks, based on geographic data, that can be used for enhanced modelling of the urban pluvial flooding process. An overland flow network produced in this way comprises three types of elements: ponds, overland flow paths and sewer inlets (gullies or manholes). Ponds represent depressions in the urban surface, i.e. flood-vulnerable areas, and flow paths represent the routes through which water flows over the terrain surface, linking, *inter alia*, ponds and sewer inlets. Such an overland flow network can then be coupled with the model of the sewer (underground) network in order to accurately simulate the dynamic interactions between these two networks (overland and underground ones), thus enabling the simulation of the hydraulic performance of urban drainage systems during flooding events. The final development of the AOFD methodology took place at Imperial College London (Boonya-aroonnet *et al.* 2007).

Two-dimensional (2D) models, based on a mesh of triangular or rectangular elements covering the urban surface, also rely on DEM information and are already available (e.g. DHI 2011; MicroDrainage 2011; Innovyze 2012). These models are, generally, more accurate; however they are significantly more computationally (time) demanding (Leitão *et al.* 2010) when compared with 1D models. The simulation run times of 2D models are highly dependent on the number of 2D mesh elements that represent the terrain surface. Overland flow simulation in urban areas require a detailed terrain surface representation, i.e. a large number of 2D mesh elements, which can lead to long simulation run times using conventional computers, not acceptable, for example, for real-time urban pluvial flood forecasting applications. Recent developments, such as the Graphics Processing Unit (GPU) technology, have been used to reduce 2D overland flow simulation run times (e.g. Kalyanapu *et al.* 2011; Innovyze 2012). A different approach was presented by Simões *et al.* (2011) in which 1D and 2D models are combined to simulate the overland flow, thus reducing the number of 2D mesh elements representing the catchment surface and, consequently, reducing the simulation run times.

Despite the benefits of 2D models to simulate overland flow, use of 1D models is still of interest for a number of flooding simulation purposes, such as early flood warning (Leitão *et al.* 2010) and emergency management. In this paper, the overland flow paths delineated are presented in the way they are used in 1D models.

When compared with overland flow networks in natural catchments, overland flow networks in urban catchments are often more complex, due to the number of man-made features (e.g. buildings, kerbs), which can significantly change the pattern of flow. In fact, both natural and man-made surface features have to be considered when modelling overland flow in urban areas. Hence DEM horizontal resolution (cell size for raster DEMs) has to be high enough to allow the accurate representation of buildings, roads, and other urban features affecting surface flow. DEM cell sizes should be smaller than 5 m (Mark *et al.* 2004); a 1–2-m cell size is preferable (Prodanović *et al.* 1994). Vertical resolution is also important when representing urban areas; street kerbs, for example, have a relevant role in overland flow routes; therefore, the vertical resolution should be higher than or equal to 0.10 m. According to these criteria, DEMs generated from contour lines and spot height points can be considered as representing the lower limit of the DEM resolution requirements. Other techniques, such as LiDAR (Light Detection and Ranging), that are able to generate DEMs of much higher resolution are, however, preferred. These three types of DEM, i.e. contour DEM, LiDAR DEM, and the SRTM (Shuttle Radar Topography Mission) DEM have been used by Leitão *et al.* (2009) to analyse the effect of DEM resolution on the overland flow network generated by the methodology developed by Maksimović *et al.* (2009).

One of the problems in implementing the AOFD methodology is that flow obstacles in DEMs, such as man-made features or DEM errors (e.g. pit cells and flat areas), significantly affect the generation of overland flow networks. According to Lindsay & Creed (2006) the errors obtained during DEM-based flow path delineation using high-resolution DEMs (e.g. 5×5 m or higher resolution) increase as DEM resolution increases due to increase of detail represented in the DEM, and also DEM errors; the increased detail represent, for example, street kerbs and benches, that will affect flow path delineation. Conventional DEM-based overland flow path delineation methods (e.g. O'Callaghan & Mark 1984; Fairfield & Leymarie 1991; Costa-Cabral & Burges 1994; Tarboton 1997) do not produce results of sufficient accuracy when using high-resolution terrain representation, e.g. using LiDAR DEMs. The common solution to this problem is to firstly create a 'hydrologically correct DEM' (Maidment & Djokic 2000), i.e. the DEM without pits and flat areas. This is a common procedure in hydrology for modelling large natural catchments; a number of pit removal techniques is available (Tianqi *et al.* 2003) and implemented in GIS packages, for example, in IDRISI (Eastman 2006). When such procedures are applied to urban DEM, they produce a number of artificial 'tunnels' through the buildings, walls and even between the streets, which, consequently, may substantially influence the resulting flow paths.

This paper presents three enhanced methods used in the DEM-based delineation of improved overland flow networks. These methods were developed to resolve the problems originated by DEM representation of urban artefacts (e.g. buildings, street kerbs) and DEM errors (e.g. pit cells and flat areas) that constitute obstacles to flow and stop the delineation process. In this paper, the results obtained using these enhanced methods are compared with the results obtained using two conventional DEM-based overland flow path delineation methods in order to evaluate their benefits.

METHODOLOGY

A semi-synthetic test DEM was used in the study presented in this paper to compare five DEM-based overland flow path delineation methods. Two of the tested flow path delineation methods, the *rolling ball* (Prodanović 1999) and *bouncing ball* (Boonya-aroonnet *et al.* 2007) methods, can be considered as conventional methods. These methods are used in this study to identify some of the main delineation issues when they are applied in urban areas and/or with low-quality DEMs. To deal with these issues, three new and enhanced methods were developed; they are called: (i) *bouncing ball and buildings* method; (ii) *bouncing ball and A** method; and (iii) *sliding ball/water accumulation* method. These three methods are described in detail in this section.

The quality of the results obtained using the different DEM-based flow path delineation methods is assessed and visually compared by analysing the flow paths geometry in plan view and based on the Hausdorff distance metric (Hangouët 1995). The Hausdorff distance is a measure to compare geographic subsets of a metric space and is defined as the maximum distance of a subset to the nearest point in the other subset (see Equation (1)):

$$h(X,Y) = \max_{x\in X}\left\{\min_{y\in Y}\{||x-y||\}\right\} \quad (1)$$

where X and Y are subsets (of points, i.e. lines) and x and y are points of subsets X and Y, respectively. Two subsets are close in terms of the Hausdorff distance if every point of either subset is close to some point of the other subset. In this particular case, the Hausdorff distance metric is used in order to compare overland flow paths (i.e. polylines).

Test DEM

A semi-synthetic test DEM was created to evaluate the performance of the two conventional versus the three enhanced overland flow path delineation methods presented in this paper. The semi-synthetic test DEM represents a square area 100 m long and 100 m wide with 1 m horizontal resolution, as illustrated in Figure 1. It is a small area selected from a hydrologically corrected (Burrough & McDonnell 1998) real DEM (background DEM) taken from the Alcântara (Lisbon, Portugal) catchment (Leitão 2009). In order to create an obstacle to the flow and simulate an urban feature (such as a small building superimposed on to the DEM), a 5×10 cell rectangle area was raised for 10 m.

Using a semi-synthetic test DEM to test and compare the results obtained using the flow path delineation methods has the main advantage of not having unexpected factors involved in the delineation errors other than the one specifically created to simulate a flow obstacle (urban feature or DEM error). Simultaneously, as the selected background DEM is part of a real DEM and since it was previously

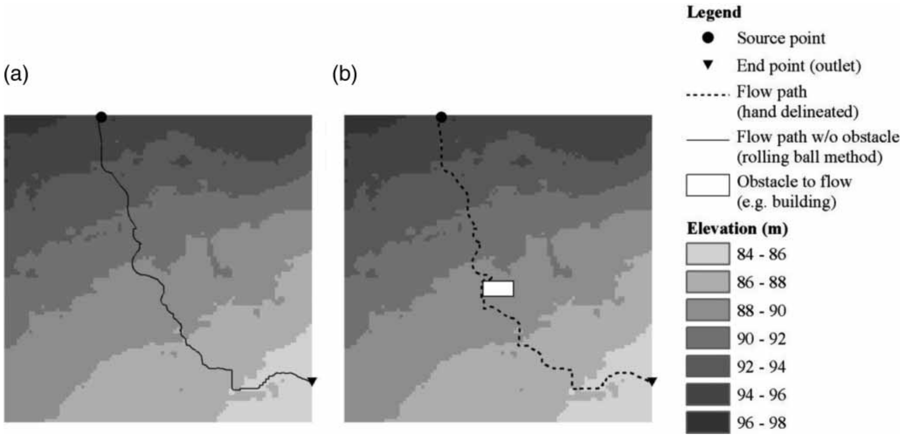

Figure 1 | Semi-synthetic test DEM used to test the conventional and enhanced flow path delineation methods; (a) DEM and flow path (*rolling ball* method) without obstacle; (b) semi-synthetic test DEM with artificial flow obstacle (e.g. building) and non-automatic delineated flow path (i.e. manual delineation based on using elevation points and contours).

hydrologically corrected, the results obtained using the semi-synthetic test DEM should be similar to the ones obtained using real DEMs.

A flow path starting point was also identified in the DEM (see Figure 1). This point represents a sewer manhole from which water can leave the underground sewer system and reach the surface drainage system when the underground sewer system becomes surcharged.

Conventional overland flow path delineation methods

The conventional flow path delineation methods considered in this study are called the *rolling ball* and *bouncing ball*. The *rolling ball* method was originally developed by Prodanović (1999) and is a revised version of the aspect-driven routing algorithm developed by Lea (1992); a similar version of this concept was also applied in 2D flood routing (Beffa 1998; Beffa & Connell 2001). This version was developed in order to delineate overland flow paths while taking into account the requisites of urban environments. The method sets the following criteria to define the end of the flow path delineation process: (i) flow path enters a pond polygon previously delineated using the methodology developed by Maksimović *et al.* (2009); (ii) flow path reaches a manhole location; or (iii) flow path reaches a sub-catchment outlet.

The *bouncing ball* method was presented by Boonya-aroonnet *et al.* (2007) in order to solve some of the issues of the *rolling ball* method, namely the incompleteness of flow paths due to DEM flow obstacles. The *rolling ball* and the *bouncing ball* methods are described in what follows.

Rolling ball method

The *rolling ball* flow routing method (Prodanović 1999) is based on the aspect vector of the terrain surface. It simulates flow movement across a planar surface in the direction of the steepest slope (Wilson *et al.* 2008). Figure 2(a) illustrates the flow path delineated using the *rolling ball* method. As can be seen, the flow path that starts at the top of the image stops close to the flow obstacle; this is caused by a pit cell/terrain depression problem, originated by the obstacle to the flow (e.g. a building).

Bouncing ball method

The *bouncing ball* method (Boonya-aroonnet *et al.* 2007) is an attempt to resolve the delineation stopping problem when the rolling ball method reaches a flow obstacle (e.g. man-made feature, pit cell or flat area) and stops. This method searches for a cell with a lower elevation than the stopping cell within a defined distance from the stopping cell, i.e. inside a buffer area. If a lower cell is found within the buffer area, then the stopping cell is linked to the lower cell by a straight line. After this step, the delineation by the rolling ball method is resumed from this lower cell.

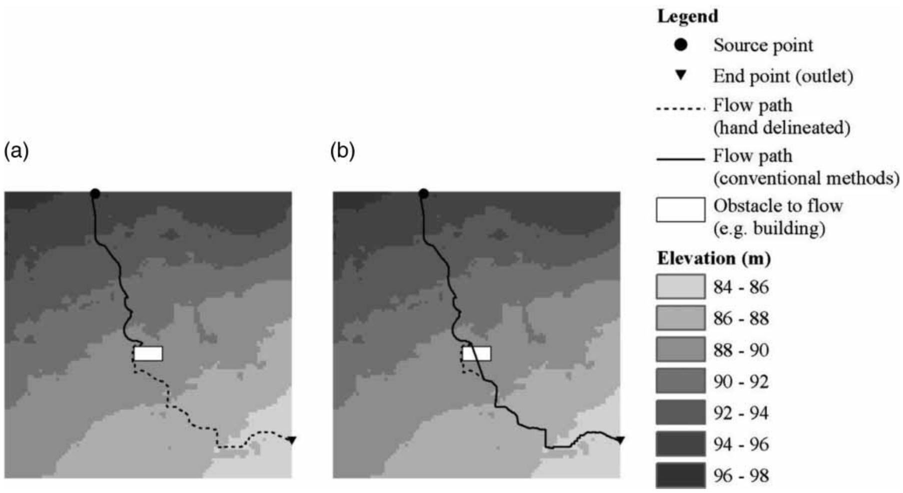

Figure 2 | Example of flow paths obtained using (a) the *rolling ball* and (b) *bouncing ball* methods.

This procedure is repeated until a termination criterion is met.

The *bouncing ball* method solves the problem of the flow path delineation process stopping when it reaches a flow obstacle, creating two new issues: (i) the line which links the stopping cell to the lower cells can cross buildings, and (ii) in some cases, the line is too long, and therefore does not represent an overland flow path realistically. The problem of the lines crossing buildings is illustrated in Figure 2(b).

The size of buffer area largely depends on the quality of the DEM. If the DEM is 'noisy', i.e. with significant number of pit cells and flat areas, the buffer area has to be larger. The best method to assess the size of the buffer area is to find for which aggregated (averaged) DEM pixel size the slope direction is gentle and continuous; the buffer area can then be defined as two or three times that pixel size. Another method is simple by trial and error: start with the buffer area three to five times the DEM pixel size, and then delineate flow paths. If not all paths are finished, the buffer area must be enlarged.

Enhanced overland flow path delineation methods

The *rolling ball* method will produce good results in delineation of flow paths using hydrologically corrected DEMs. However, most available DEMs will have errors like pit cells, flat areas and hollows. In addition, in urban areas there are a significant number of man-made features that act as flow obstacles which occasionally contribute to stop the overland flow path delineation process, leaving flow paths incomplete.

The enhanced methods presented in this paper were developed to solve the problems identified in the previous section. These new methods increase the reliability of the conventional DEM-based overland flow path delineation methods. With the proposed methods, the flow path delineation process continues if it encounters a problem (e.g. pit cell or flow obstacle) before reaching one of the flow path delineation termination criteria. In addition, the proposed methods avoid flow paths crossing buildings or other flow obstacles.

In most of the cases, it is difficult to distinguish between DEM errors and real features because the DEM source is usually unknown, so using methods to enhance DEMs by removing all pit cells, all depressions and all flat areas can generate erroneous surface representations. This fact further emphasises the need for development of alternative DEM-based overland flow path delineation methods to overcome these problems without the need for changing DEM cells' elevation (like, for example, using the *Pit Removal* function available in IDRISI (Eastman 2006) or the *Fill* function available in ArcGIS (ESRI 2006)).

The new proposed methods, the *bouncing ball and buildings*, *bouncing ball and A**, and *sliding ball/water accumulation* methods, are used together with the *rolling* *ball* method when this method stops the delineation process due to a DEM error or a real flow obstacle. Tests and comparisons between the conventional and enhanced methods are performed using the semi-synthetic test DEM presented above.

Bouncing ball and buildings method

As shown in Figure 2(b), the *bouncing ball* method requires further upgrades in order to solve the problem of flow paths crossing buildings (or other flow obstacles). The first enhanced method developed in this study to solve this problem makes use of a vector polygon layer, or raster layer, representing flow obstacles. The polygons (or raster layer specific values representing flow obstacles) are used to validate the line linking the flow path stopping cell and the lower elevation cell (within the buffer area), and to check if the line crosses a building or not. This new method divides the linking line into small line segments (e.g. of 1 m length), and detects whether any of its segment end nodes are within the flow obstacle area (e.g. a building). If one of these nodes is within a flow obstacle representation (vector polygon or raster specific value), this indicates that the linking line crosses a flow obstacle. The linking line is then discarded and a new lower elevation cell is searched within the buffer area.

When a linking line that does not cross a flow obstacle is found, the flow path delineation continues from the lower cell using the *rolling ball* method. The flowchart showing how the *bouncing ball and buildings* method work is presented in Figure 3.

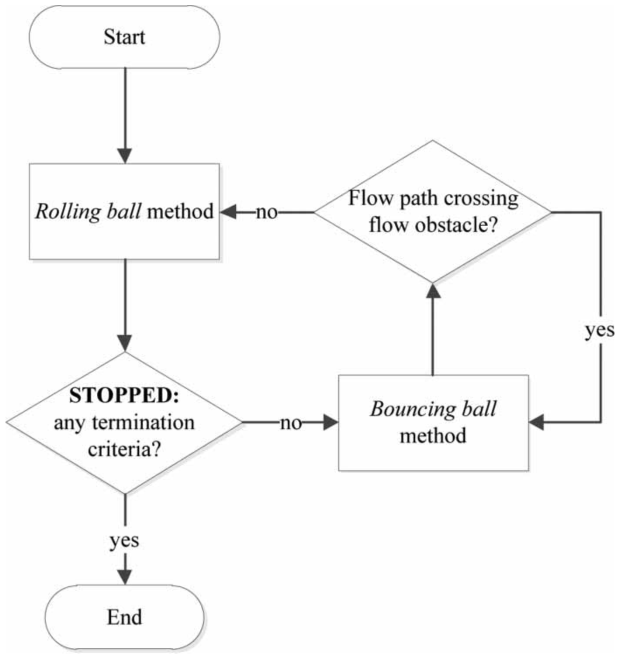

Figure 3 | Flowchart of *bouncing ball and buildings* method.

Bouncing ball and A^* method

The *bouncing ball* and A^* method is based on the implementation of the *bouncing ball* concept together with a least-cost algorithm. Least-cost (or optimisation) algorithms are used to search least-cost paths between a starting node and a goal node of a graph. It should be noted that in this context, a graph refers to a collection of nodes and a collection of edges that connect pairs of nodes. The least-cost algorithm used in this enhanced method is the A^* algorithm (Hart *et al.* 1968). The A^* algorithm used in order to improve the *bouncing ball* method was adapted to use DEMs as graphs. In this case, the centre of the raster cells represents graph nodes, and the graph edges are virtual edges that link the eight neighbouring cells. The cost associated with the movement between two cells is calculated based on the distance and on the elevation differences between two cells. The cost is directional, i.e. it is more costly to go up than to go down. This ensures that the algorithm searches for descending flow paths whenever possible, avoiding the buildings that are represented by a high elevation.

In the event that the flow path method stops, i.e. when flow path delineation hits an obstacle and stops, the first step is to identify a cell within the buffer area lower than the one where the flow path delineation has stopped. The A^* least-cost algorithm and DEM elevation is then used to link the flow path delineation stopping cell and the lower cell. In this case, it is essential to have all buildings' elevation represented in the DEM. The A^* algorithm is coupled with the *rolling ball* and *bouncing ball* methods in the way presented in Figure 4.

Sliding ball/water accumulation method

The *sliding ball/water accumulation* method combines the *rolling ball* flow path delineation method with another

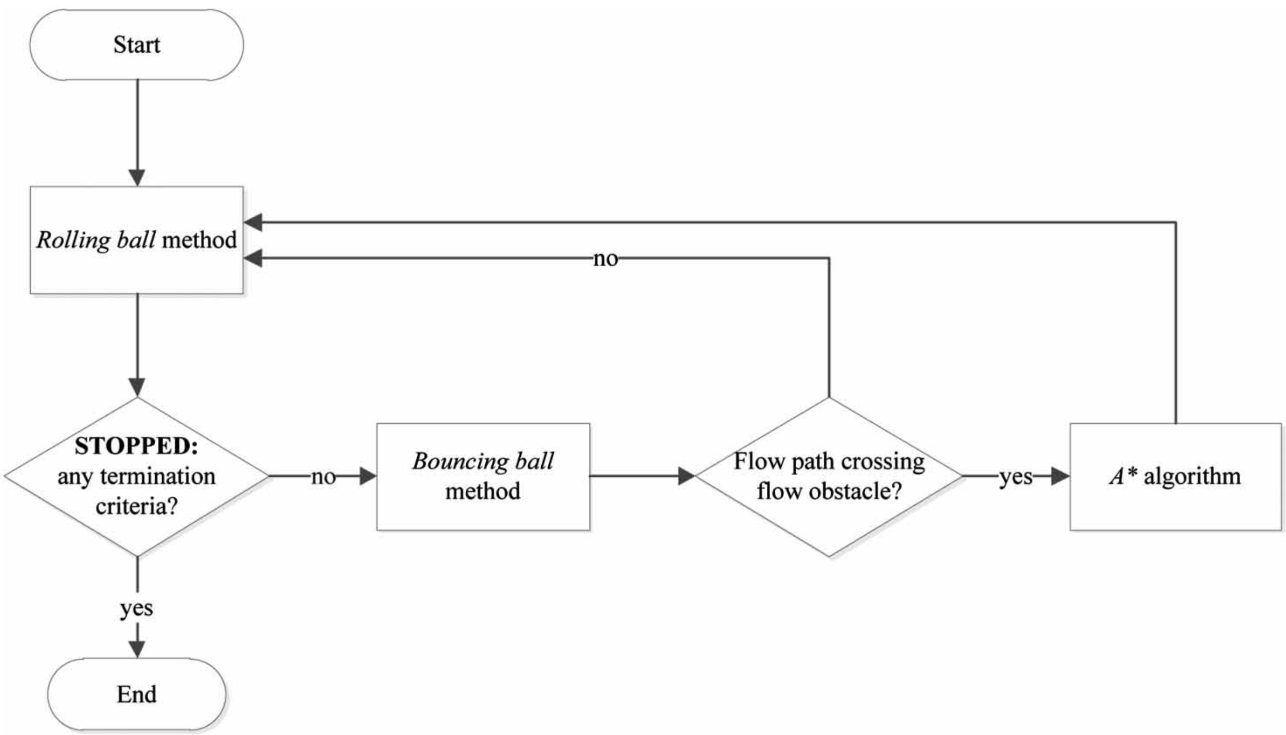

Figure 4 | Flowchart of *bouncing ball and A** method.

improvement to resolve the problem of incomplete flow paths. If and when the *rolling ball* delineation method stops, the *sliding ball/water accumulation* method searches for the lowest cell among the eight neighbouring cells. The lowest neighbouring cell may have higher elevation than the cell where the flow path delineation stopped. After each move to the lowest of the eight neighbouring cells, the flow path delineation method uses the *rolling ball* flow path delineation method to re-start and continue the flow path delineation process. If the re-start is unsuccessful, the flow path is moved to the lowest neighbouring cell and so forth.

The concept behind the *sliding ball/water accumulation* method is similar to the water accumulation phenomenon in depressions; the water accumulates within a depression until it finds an exit point from which it can continue to flow downstream. Using the *sliding ball/water accumulation* method, the movement from the pit cell to the lowest neighbouring cell is comparable to the sink cell water fill process; this method is best suited for small pit cell DEM errors but can also be used to delineate overland flow paths in urban areas (i.e. around flow obstacles such as buildings, as shown in the results section). A flowchart illustrating the steps of this method is presented in Figure 5.

This method solves the problem of flow path delineation process stopping due to flow obstacles (or terrain depression). However, it does not ensure that the flow path obtained does not cross flow obstacles. In some cases, the lowest neighbouring cell can represent either the flow obstacle or part of the already delineated/existing flow path. In these cases, the flow path does not move to the neighbouring cell already marked as flow path in order to avoid infinite loops, but to a neighbouring cell that represents a flow obstacle (with higher elevation).

RESULTS

In Figure 6, an illustration of the results obtained by the *bouncing ball and buildings* method is shown. The dashed line represents the non-automatic delineated flow path and the solid line represents the flow path obtained using the *bouncing ball and buildings* method.

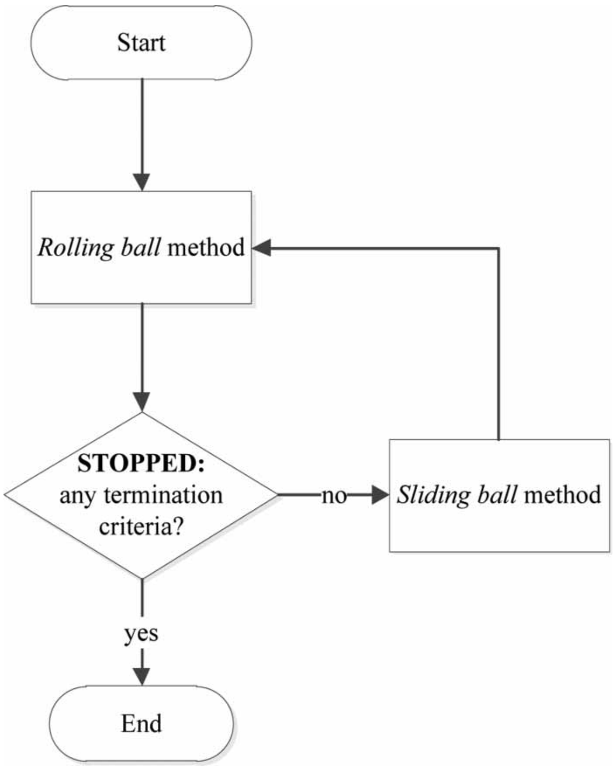

Figure 5 | Flowchart of *sliding ball/water accumulation* method.

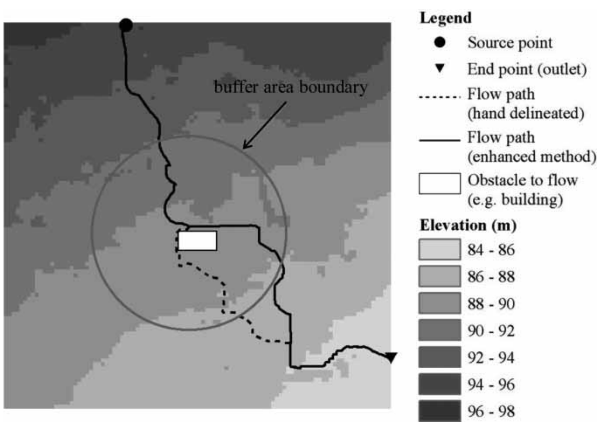

Figure 6 | Example of flow delineation result obtained using the *bouncing ball and buildings* method.

Although the results illustrated in Figure 6 show that the flow path is completed and does not cross the flow obstacle (a small building, in this case), it is clear that the flow path is significantly diverted from the point where its delineation would stop using the *rolling ball* method (see Figure 2(a)). This is due to the fact that the lower cell found within the 25 m buffer area that allows the flow path to not cross the building is located far from the flow obstacle (a 25 m radius buffer area was selected for the used DEM after a few trials as a compromise between the need to have sufficient area to ensure an existing cell with lower elevation than stopping cell; a smaller area could result in no cells with lower elevation than the stopping cell) and the results accuracy, larger buffer areas would result in larger differences between the non-automatic delineated flow path and the resulting flow path).

Figure 7 shows the results obtained using the *bouncing ball and A** method; the flow obstacle was not crossed by the flow path, and the flow path follows the terrain elevation, avoiding, as much as possible, movements in the uphill direction.

A problem that can occur when using the *bouncing ball*-based methods (i.e. *bouncing ball and buildings* and *bouncing ball and A* methods*) is that in some cases no lower elevation cells are found within the buffer area; in this case, the flow path will not be completed.

In Figure 8, the flow path obtained using the *sliding ball/water accumulation* method is shown. This method does not avoid crossing flow obstacles. However, unlike the enhanced *bouncing ball*-based methods (*bouncing ball and buildings* and *bouncing ball and A** methods), the *sliding ball/water accumulation* method also solves the problem of not finding a lower cell within the buffer area.

Four sets of flow path cross-sections were analysed in order to compare the flow paths obtained using

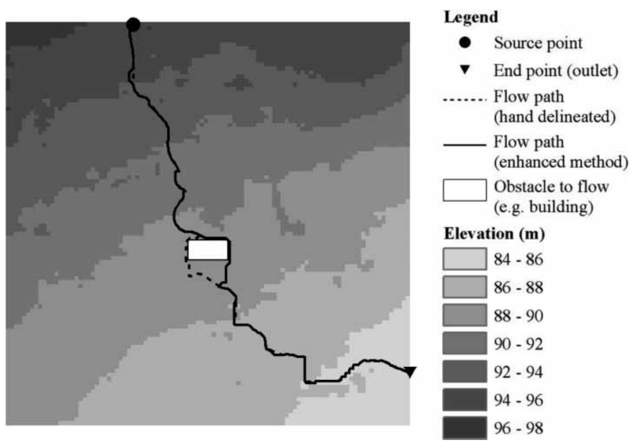

Figure 7 | Example of flow path delineated using the *bouncing ball and A** method.

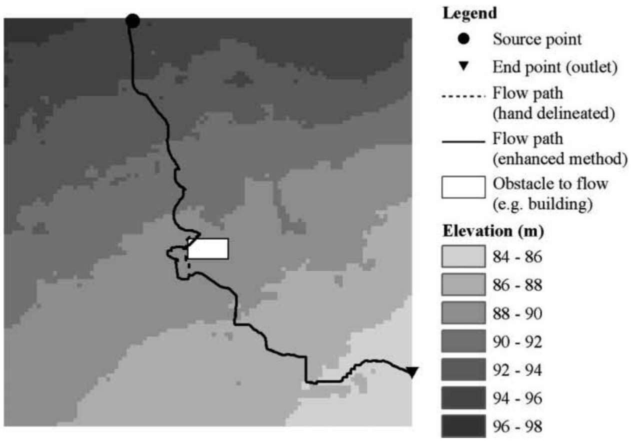

Figure 8 | Example of flow path delineated using the *sliding ball/water accumulation* method.

the enhanced flow path delineation methods with the hand-delineated one (Figure 9). The cross-sections chosen to perform the comparison are located at 1/4, 1/2 and 3/4 of the length of each flow path after the stopping point (flow paths are different only after the stopping point).

Using the hand delineated (Manual) flow path cross-sections as reference, the major differences are observed for cross-sections of the flow path obtained using the *bouncing ball and buildings* method; these differences are more significant for the 1/4 and 1/2 cross-sections.

DISCUSSION AND CONCLUSIONS

The results obtained using the enhanced overland flow path delineation methods presented in this paper show that all three methods can find a reasonable way out of problematic DEM areas (e.g. real flow obstacles, such as buildings, kerbs or other man-made features and DEM errors, such as pit cells and flat areas). These methods will, thereby increase the reliability of the *rolling ball* flow path delineation method by providing complementary solutions in problematic cases. By implementing these methods, the completion of the flow path, for the whole catchment, can be achieved. Table 1 presents the length and slope of the flow paths generated using the conventional and enhanced flow path delineation methods and the semi-synthetic test DEM and the Hausdorff distance calculated between the non-automatic delineated flow path and each of the flow paths obtained using the conventional and enhanced methods, taking into account the DEM flow obstacle.

The length of the flow paths obtained using all delineation methods are similar (see Table 1), except for the flow path delineated using the *rolling ball* method; this is expected because this method is the only one that does not produce a complete flow path. The flow path obtained using the *bouncing ball* method is complete but does cross

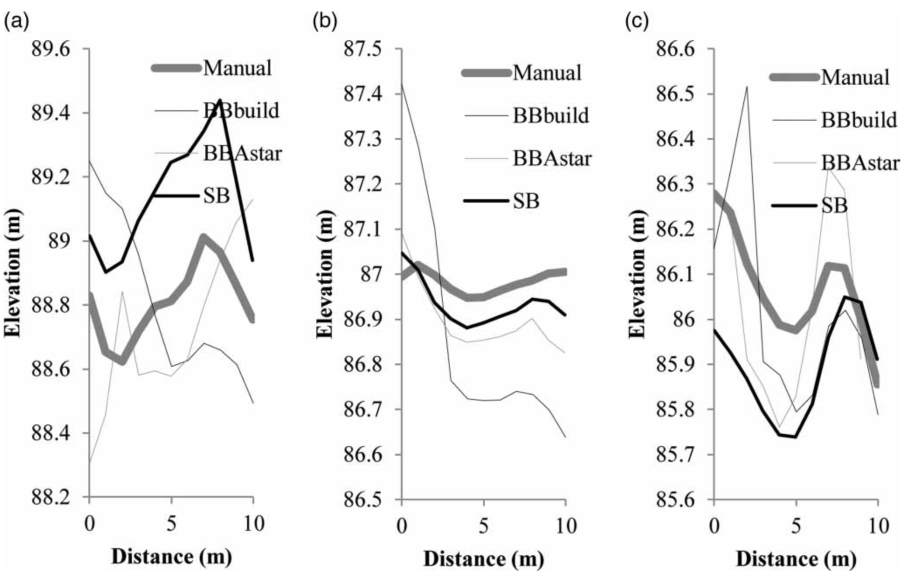

Figure 9 | Flow paths cross-section elevation profiles at (a) 1/4 length; (b) 1/2 length; and (c) 3/4 length. (Manual – hand delineated; BBbuild – *bouncing ball and buildings* method; BBAstar – *bouncing ball and A** method; SB – *sliding ball/water accumulation* method).

Table 1 | Summary of flow path delineation results obtained using the conventional and improved flow path delineation methods and the semi-synthetic test DEM

Flow path delineation method	Completeness	Cross obstacle?	Length (m)	Slope (%)	Hausdorff distance (m)
Non-automatic delineation (hand delineated)	–	–	151.2	7.06	–
Rolling ball	No	–	64.3	[a]	[a]
Bouncing ball	Yes	Yes	148.7	7.17	6.6
Bouncing ball and buildings	Yes	No	155.9	6.84	15.6
*Bouncing ball and A**	Yes	No	157.8	6.76	9.7
Sliding ball/water accum.	Yes	Yes	173.9	6.14	3.9

[a]The Slope and Hausdorff distance were not calculated because the flow path delineation was not complete.

the flow obstacle. The slope was calculated based on the elevation of the starting and ending points of the flow path and its length. Slope variations among the obtained flow paths using the different methods are explained solely by the differences in length of the flow paths, as starting and ending points are the same for all the complete flow paths.

Two of the three enhanced methods presented in this paper (*bouncing ball and buildings* and *bouncing ball and A** methods) resolve the problem of flow path completeness and crossing flow obstacles problem. The third method, the *sliding ball/water accumulation* method solves the problem of flow path completeness only. Nevertheless, some minor issues were also observed in the results obtained using the enhanced flow path delineation methods. The results obtained using the *bouncing ball and buildings* method showed a significant diversion of the flow path in comparison to the non-automatic delineated flow path and the flow paths obtained using all other delineation methods; this is clearly visible in Figure 6 and is confirmed by the relatively high value of the calculated Hausdorff distance (15.6 m), as shown in Table 1. On the other hand, the flow path delineated using the *bouncing ball and A** method showed a smaller Hausdorff distance value, indicating that no significant diversion occurs when compared with the non-automatic delineated flow path, with the advantage of not crossing the flow obstacle. Potential problems for *bouncing ball*-based enhanced methods can occur when no cells with an elevation lower than the stopping cell exist within the buffer area; these problems can be resolved using the *sliding ball/water accumulation* method.

The Hausdorff distance calculated for the flow path delineated using the *sliding ball/water accumulation* method was 3.9 m, the smallest value among the values obtained by the flow path delineation methods considered in this study. The *sliding ball/water accumulation* method is based on a physical hydraulic explanation: water accumulating in a depression. However, the differences in the length are slightly higher than the differences obtained for the *bouncing ball*-based enhanced methods.

Computational time for flow paths delineated using the three enhanced flow path delineation methods in this study was similar and very short (less than 1 s). However, for longer paths in which the delineation using the rolling ball algorithms stops a few times, the delineation process can take a few minutes; this was experienced in several real cases (Allitt *et al.* 2009; Leitão 2009).

In order to deal with the cases in which a lower cell does not exist within the buffer area when using an improved *bouncing ball* method, the enhanced methods can be combined; this integration is currently being developed by the authors.

Although the flow paths delineated using the enhanced methods presented in this paper are diverted from the non-automatic delineated flow path, in all three cases the resulting flow path finishes at the same sub-catchment outlet, the sub-catchment exit point. If a flow path delineated using one of the enhanced methods would jump too far from the natural flow path, it could enter into a neighbouring sub-catchment and, in that case, the exit point would not be the same; this can happen when using the *bouncing ball*-based methods, especially in the case of long/large flow obstacles, such as walls and long buildings or when the buffer area set to search for the lower cell is too large. If this occurs, the resulting overland flow network may not represent the real overland flow conditions.

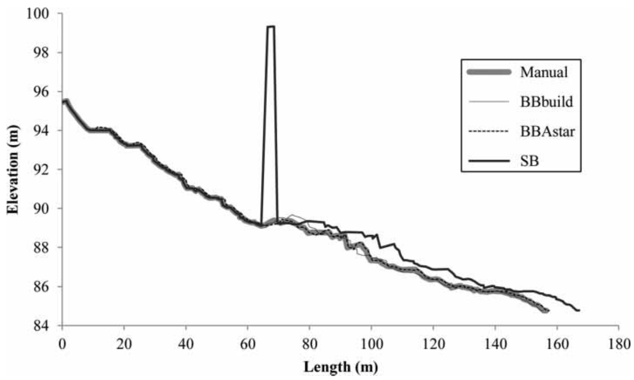

Figure 10 | Flow paths longitudinal elevation profiles.

Regarding the flow path longitudinal profile, due to the 'jumps' of the bouncing ball-based methods or the movements towards the neighbouring cells of the sliding ball/water accumulation method, it is not always possible to guarantee a completely descending longitudinal profile (see Figure 10). Although this could be considered a disadvantage in hydraulic modelling terms (i.e. when considering the flow path as input to urban drainage models) because it does not represent the real path, it is not a problem as long as the average flow path slope is calculated based on the flow path length and difference between the elevations of the flow path initial and end points.

Results presented in this paper show that the enhanced overland flow path delineation methods are capable of handling problematic DEM areas. In addition to the methods comparison results using a synthetic DEM presented in this paper, these methods were used in full-scale cases (Allitt *et al.* 2009), with a multitude of buildings, and proved to be reliable and produce realistic results. Despite the issues mentioned above, the reliability of the generation of overland flow networks process is significantly increased. This advance in automatically generating 1D overland flow networks in problematic DEM areas will strengthen the role of the 1D/1D urban pluvial flood modelling, sustaining their role along the application of 1D/2D models.

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REFERENCES

Adeyemo, O. J., Maksimović, Č., Boonya-aroonnet, S. & Leitão, J. P. 2008 Sensitivity analysis of surface runoff generation for pluvial urban flooding. In: *11th International Conference on Urban Drainage*, Edinburgh, UK.

Allitt, R., Blanksby, J., Djordjevic, S., Maksimovic, C. & Stewart, D. 2009 Investigations into 1D–1D and 1D–2D Urban Flood Modelling – UKWIR project. In: *WaPUG Autumn Conference*, Blackpool, UK.

Beffa, C. 1998 Two-dimensional modelling of flood hazards in urban areas. In: *3rd International Conference on Hydroscience and Engineering*, Berlin, Germany.

Beffa, C. & Connell, R. J. 2001 Two-dimensional flood plain flow – Part I: Model description. *Journal of Hydrologic Engineering ASCE* **6**, 397–405. Errata.

Boonya-aroonnet, S., Maksimović, Č., Prodanović, D. & Djordjević, S. 2007 Urban pluvial flooding: development of GIS based pathway model for surface flooding and interface with surcharged sewer model. In: *6th International Conference on Sustainable Techniques and Strategies in Urban Water Management*, Lyon, France.

Burrough, P. A. & McDonnell, R. A. 1998 *Principles of Geographical Information Systems*, 2nd edition. Oxford University Press, Oxford, 352 pp.

Costa-Cabral, M. & Burges, S. J. 1994 Digital Elevation Model Networks (DEMON): a model of flow over hillslopes for computation of contributing and dispersal areas. *Water Resources Research* **30**, 1681–1692.

DHI 2011 MIKE URBAN, http://www.mikebydhi.com/Products/Cities/MIKEURBAN/UrbanFlooding.aspx. (Accessed online 28 October 2011).

Djordjević, S., Prodanović, D. & Maksimović, Č. 1999 An approach to simulation of dual drainage. *Water Science and Technology* **39**, 95–103.

Eastman, J. R. 2006 *IDRISI Andes*. Clark University, Worcester, MA, USA.

ESRI 2006 *ArcGIS Desktop Help*. Environmental Systems Research Institute Inc., Redlands, CA, USA.

Fairfield, J. & Leymarie, P. 1991 Drainage networks from Grid Digital Elevation Models. *Water Resources Research* **27**, 709–717.

Hangouët, P. 1995 Computation of the Hausdorff distance between plane vector polylines. In: *12th International Symposium on Computer-Assisted Cartography*, Charlotte, NC, USA.

Hart, P. E., Nilsson, N. & Raphael, B. 1968 A formal basis for the heuristic determination of minimum cost paths. *IEEE Transactions of Systems Science and Cybernetics* **SSC-4** (2), 100–107.

Innovyze 2011 *Infoworks CS v10.0 Help*. Innovyze Ltd, Wallingford, UK.

Innovyze 2012 Infoworks CS technical review. Available from: http://www.innovyze.com/products/infoworks_cs/infoworks_cs_technical_review.pdf (Accessed online 17 February 2012).

Kalyanapu, A. J., Shankar, S., Pardyjak, E. R., Judi, D. R. & Burian, S. J. 2011 Assessment of GPU computational enhancement to a 2D Flood Model. *Environmental Modelling Software* **26**, 1009–1016.

Kinouchi, T., Kuriki, M. & Tanaka, Y. 1995 Prediction of local inundation in an urbanized watershed. In: *2nd International Conference on Innovative Technologies in Urban Storm Drainage*, Lyon, France.

Lea, N. J. 1992 An aspect driven kinematic routing algorithm. In: *Overland Flow: Hydraulics and Erosion Mechanics* (A. Parsons & A. Abrahams, eds). Chapman and Hall, New York, USA, pp. 393–407.

Leitão, J. P. 2009 Enhancement of Digital Elevation Models and Overland Flow Path Delineation Methods for Advanced Urban Flood Modelling. PhD Thesis, Imperial College, London, UK.

Leitão, J. P., Boonya-aroonnet, S., Prodanović, D. & Maksimović, Č. 2009 The influence of Digital Elevation Model resolution on overland flow networks for modelling urban pluvial flooding. *Water Science and Technology* **60** (12), 3137–3149.

Leitão, J. P., Simões, N. E., Maksimović, Č., Ferreira, F., Prodanović, D., Matos, J. S. & Sá Marques, A. 2010 Real-time forecasting urban drainage models: full or simplified networks? *Water Science and Technology* **62** (9), 2106–2114.

Lindsay, J. B. & Creed, I. F. 2006 Distinguishing actual and artefact depressions in digital elevation data. *Computers & Geosciences* **32**, 1192–1204.

Maidment, D. R. & Djokic, D. 2000 *Hydrologic and Hydraulic Modeling Support with Geographic Information Systems*. ESRI Press, Environmental Systems Research Institute, Inc., Redlands, CA, USA.

Maksimović, Č., Prodanović, D., Boonya-aroonnet, S., Leitão, J. P., Djordjević, S. & Allitt, R. 2009 Overland flow and pathway analysis for modelling of urban pluvial flooding. *Journal of Hydraulic Research* **47**, 512–523.

Mark, O., Weesakul, S., Apirumanekul, C., Boonya-aroonnet, S. & Djordjević, S. 2004 Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology* **299**, 284–299.

MicroDrainage 2011 WinDes W12.6. FloodFlow datasheet. Available from: http://www.microdrainage.co.uk/.../FloodFlow_Datasheet_W12_6.pdf. (Accessed online 28 October 2011).

O'Callaghan, J. F. & Mark, D. M. 1984 The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics and Image Processing* **28**, 323–344.

Pitt, M. 2008 The Pitt Review - Lessons learned from the 2007 summer floods. Technical report, UK Cabinet Office, London, UK. Available from: http://webarchive.nationalarchives.gov.uk/20100807034701/http:/archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html (Accessed online 17 August 2011).

Prodanović, D. 1999 Advances in Hydroinformatic Support to Urban Runoff. PhD Thesis, University of Belgrade, Serbia (In Serbian).

Prodanović, D., Djordević, S. & Maksimović, Č. 1994 Interfacing Auto-CAD updated by GIS functions with simulation models for urban infrastructure projects. In: *The European Conference and Exhibition on Remote Sensing and GIS in Urban Waters UDT'94*, Moscow, Russia.

Simões, N., Ochoa, S., Leitão, J. P., Pina, R., Sá Marques, A. & Maksimović, Č. 2011 Urban drainage models for flood forecasting: 1D/1D, 1D/2D and hybrid models. In: *12th International Conference on Urban Drainage*, Porto Alegre, Brazil.

Tarboton, D. G. 1997 A new method for the determination of flow directions and upslope areas in Grid Digital Elevation Models. *Water Resources Research* **33** (2), 309–319.

Tianqi, A., Takeuchi, K., Ishidaira, H., Yoshitani, J. & Fukami, K. 2003 Development and application of a new algorithm for automated pit removal for grid DEMs. *Hydrological Sciences Journal* **48**, 985–997.

Wilson, J. P., Aggett, G., Deng, Y. & Lam, C. S. 2008 Water in the landscape: a review of contemporary flow routing algorithms. In: *Advances in Digital Terrain Analysis* (Q. Zhou, B. Lees & G. Tang, eds). Springler-Verlag, Berlin, Heidelberg.

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