Sensitivity Analysis of Surface Runoff Generation for Pluvial Urban Flooding

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ABSTRACT

Significant advances have been made in recent times in the domain of integrated hydraulic modelling of urban flooding. Development of a physically based model for dual drainage concept, in which urban surface is treated as a network of open channels and ponds (major system) connected to the sewer network (minor system), has been a step forward (Boonya-aroonnet et al. 2006). However, generation of reasonably realistic surface network is the main concern in this methodology (Djordjevic et al. 2005).

This paper presents the results obtained by new developed tools (Boonya-aroonnet et al. 2007) for enhancing the potential of 1D/1D modelling by more accurate GIS-based automatic generation of surface network features. The application of these tools to a real life case study is discussed.

Simplification of high resolution of LiDAR Digital Terrain Model (DTM) by re-sampling original 1x1m grid to larger sizes is necessary and sensitivity is analysed. Number of ponds removed and cumulative and discrete volume loss charts were generated and used to determine the suitable threshold values for removal of small ponds.

In generating the pathways cross-section geometry, multi-criteria optimization technique was deployed to study the sensitivity of the input parameters on the geometries generated and appropriate parameter selection process.

KEYWORDS

Pluvial urban flooding, sensitivity analysis, dual drainage, surface flow network

INTRODUCTION

The flood problems arising from urban flooding range from minor ones, such as water entering the basements of a few houses, to major incidents, where large parts of cities are inundated for several days. Most modern cities in the industrialized world have been facing small-scale local problems mainly due to insufficient capacity in their sewer systems during heavy rainstorms (Mark et al. 2004). Hence, prevention of flooding in urban areas caused by inadequate sewer systems has become an important issue. With increased property values of buildings and other structures, potential damage from prolonged flooding can easily become economically catastrophic. For instance, in the UK, during July 2007, floods have damaged nearly 30,000 homes and 7,000 businesses and have taken the lives of some people as well. Insurers think the clean-up bill will top 2 billion pounds[1]. The service fees paid by residents are used to operate and maintain urban drainage systems effectively without fear of failure, thereby keeping the level of service acceptable. However, drainage systems are designed to cope with a defined project storm, i.e. if a stronger storm happens, flood problems may occur.

[1] http://en.wikipedia.org/wiki/2007_United_Kingdom_floods

Thus, in establishing tolerable flood frequencies, the safety of the residents and the protection of their valuables must be in balance with the technical and economic restrictions (Schmitt et al 2004).

The Urban Water Research Group (UWRG) of Imperial College London have been engaged in research to enhance the potential of 1D/1D type of model by more accurate GIS-based automatic generation of surface flow characteristics such as ponds and flow pathways, cross-section geometry, connectivity, area-depth curves within the AUDACIOUS[2] and FRMRC[3] projects. The approach is based on Digital Elevation Model (DEM) and land-use images derived from high resolution and accuracy acquisition techniques. The work presented here is a contribution to the ongoing research at the group. It covers the preparation of input data and detailed investigation into the sensitivity analysis of the parameters associated with the developed tool. Simulations of the dual drainage system were carried out using InfoWorks, taking into account the surface flow network generated with the developed tool.

Figure 1 presents the overall process described in this paper. The main objectives are:

1. Investigate some of the sensitivity issues associated with the GIS based tool as reported by Boonya-aroonnet et al. (2007). This has to do with the sensitivity of the various parameters to be used in developing the appropriate overland model;
2. Using appropriate parameters based on the investigation, develop the surface network model using the GIS-Based tool. The surface pathway network for the model consists of storage nodes (with its characteristics) and links (with its shapes);
3. Introduce the output of the surface network model into commercial software, InfoWorks;
4. Simulate a 1D-1D (i.e. one-dimensional in both surface network and sewer pipe flow) urban pluvial flooding applying the dual drainage concept model in InfoWorks;
5. Investigate the potentials of the use of the GIS based tool in planning new developments especially with respect to pluvial urban flooding;
6. Identify areas for further research

METHODOLOGY TO GENERATE SURFACE FLOW NETWORK AND SIMULATE URBAN PLUVIAL FLOOD

Data Preparation

LiDAR data, in ESRI ASCII Grid format, was obtained from the Environment Agency. Data resolution is 1x1m and went through a classification and filtering processes in order to produce Digital Terrain Models (DTM) from the original Digital Surface Model (DSM).

Using ArcGIS® Desktop 9.1, IDRISI® Andes and CatchmentSIM®, the necessary project files to generate the overland flow network modelling phase of the project were created, including slope and aspect images.

Two sets of DTMs were prepared – original and smooth. Smoothening was done to remove spurious depressions and flat areas and as many problematic features as possible. About 10 iterations of the *filling* algorithm in CatchmentSim® were applied to the original DTMs to produce the smooth ones.

The original 1m resolution data from LiDAR was resampled to produce DTMs with the following cell sizes: 2x2m, 4x4m, 5x5m, 8x8m and 10x10m. This exercise was carried out for both the original and smooth data sets.

[2] Adaptable Urban Drainage – Addressing Change in Intensity, Occurrence and Uncertainty of Stormwater
[3] Flood Risk Management Research Consortium

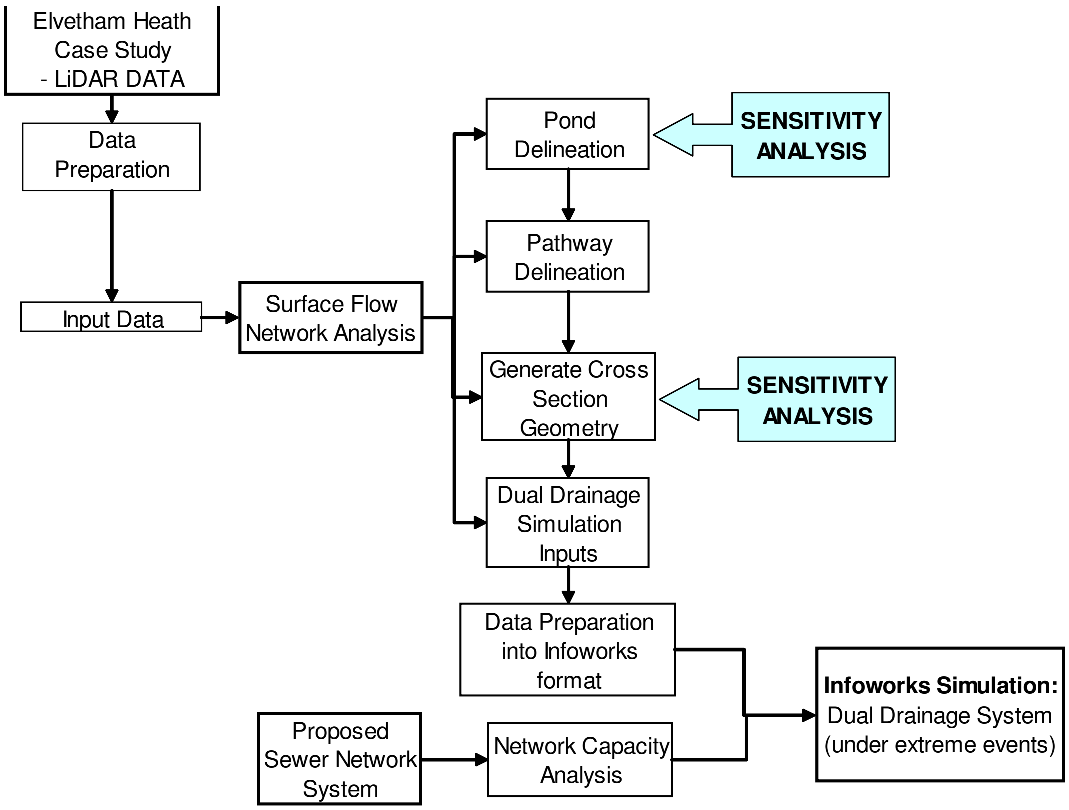


Figure 1 Overview of the Application of the GIS-Based Tool in a Case Study

Sensitivity Analysis

The sensitivity analysis was carried out on some vital input parameters of the GIS-based routines in order to determine the appropriate value parameters to obtain the best representation of overland flow. Specifically, these are the pond filtering parameters of pond delineation procedure and the parameters to generate flow pathways cross sections.

The sensitivity analysis at the pond delineation phase was carried out on all the datasets prepared, both original and smoothened. After this stage and following an analysis of the result, a DTM was chosen. Flow pathways were created using only the chosen DTM. Sensitivity analysis at the Cross Section Geometry process was conducted using the adopted DTM.

The objective of the exercise at the pond delineation module was to determine the threshold value of depth and volume parameters that ensure elimination of noise from the DTM while minimising volume loss. Combinations of volume variations of $1m^3$, $2m^3$, $3m^3$, $4m^3$ and $5m^3$ were employed with depth variations of 0.004m, 0.008m, 0.01m, 0.02m, 0.03m, 0.04m, 0.06m, 0.08m, 1.0m, 1.5m and 2.0m.

The objective of the exercise at the cross-section module was to determine the appropriate combination of the parameters such that there are a minimal number of cross sections ending up with the user pre-defined sections.

Case Study - Location and General Overview

The case study used for this project is Elvetham Heath. Elvetham Heath is an ongoing 1,868-home development in the prospering suburbs of Hampshire (UK). It is located immediately to the north of Fleet in the borough of Hart. It is bounded to the North by the M3 motorway and the Fleet motorway service area and to the South by the London/Southampton railway line. To the East is the North Hampshire Golf Club and to the West the A323. It is connected by a 40 – 80 minute train service from central London and is located 5-minute drive from the nearby town of Fleet (Figure 2).

Figure 2. Location of Elvetham Heath Fleet

The predominant land use is residential occupying 0.63km^2 of the 1.26km^2 site. Sewer system has approximately 62 manholes over the sewered area of the analysis.

RESULTS AND DISCUSSION

Pond Delineation

Without applying any filtering parameters, the number of ponds generated in the original DTM data sets range from 607 to 32,766 while that of the smoothened DTM data sets range from 137 to 3,561. A summary of the result obtained for the smoothened DTM data sets is shown in Table 1

Table 1 – Normalized Volume and Pond Loss for Smooth DTMs without applying any filter parameter

Cell Size (m)	No of Ponds (No)	Volume of Ponds (m^3)
1x1	7,303	116,158
2x2	1,865	113,995
4x4	749	105,270
5x5	501	99,961
8x8	189	94,543
10x10	137	90,516

Figure 3 shows the normalised plots showing the relationship between DTM cell size, pond loss and volume loss. From the results obtained, it can be deduced that the shift from 1x1m DTM to a 2x2m DTM, which resulted in a loss of 90% of the ponds but only 9% of the total volume, may have led to a significant reduction in noise/pit cells in the further analysis of the DTM. Thereafter, it was observed that an almost linear relationship exists between the pond loss and volume loss for the DTM with cell sizes 4x4m, 5x5m, 8x8m, and 10x10m. This may represent a more physical volume loss commensurate with the corresponding pond loss.

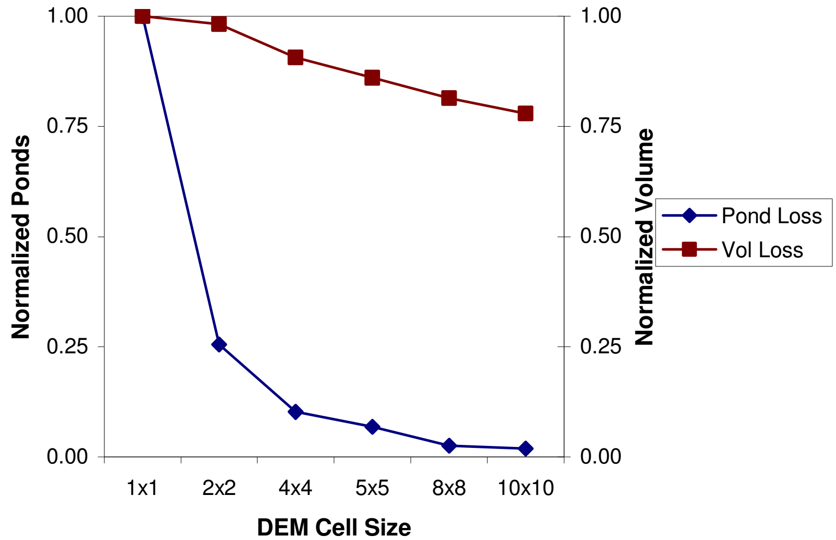


Figure 3. Normalized Volume and Pond Loss for Smoothened DTMs without applying any filter parameter

The filtering was done to remove the ponds that satisfy both depth and volume criteria but the DTM remain unchanged. Though due to the limitation in the capacity of the tool, the volume figures for the original 1x1m DTM could not be determined, similar trend was observed in the results obtained from simulations with the original DTMs.

Based on these observations, the 2x2m DTM was adopted for further detailed analysis. Figure 4 shows the spatial distribution of the ponds for the 2x2m DTM cell size and this gives a physical appreciation of the ponds, which helps to analyse the potential of flood vulnerability in the area. The choice of the 2x2m DTM is consistent with the recommendations of a cell size of between 1x1m and 5x5m DTM resolution for urban flood analysis (Mark et al 2004).

Pond Filtering

This analysis was carried out for all the datasets. Thus, volume-loss curves such as those in Figure 5 were generated. From the curves generated, three zones were identified, Zones A, B and C. In Zone A, the five volumes being tested against various depths exhibits the same trend. This may be due to the very small depth values being tested in relation to cell sizes. It is also believed that some noise is still inherent in the DTM in this zone.

In Zone B, the individual volume loss curves spread out further, reflecting their relative volume values. From each curve, there is a point where further variation in depth does not produce any change in the cumulative volume loss. This point is here referred to as the Pond Filtering Optimum Depth (PFOD). And Zone C is the zone after the PFOD for each volume curve. It was also observed that the coarser the DTM being tested, the more pronounced is Zone C as the PFOD is attained quicker.

Lisbon Data Set

To determine whether the curves and trends observed on the cumulative volume-loss charts for the Elvetham Heath data sets can be standardised for the GIS-based routine tool, the analysis was further conducted on a dataset from Lisbon (Portugal). The source of the Lisbon DTM is also LiDAR, originally in 1x1m resolution and then re-sampled to different cell sizes – 2x2m, 4x4m, 5x5m, 8x8m, and 10x10m.

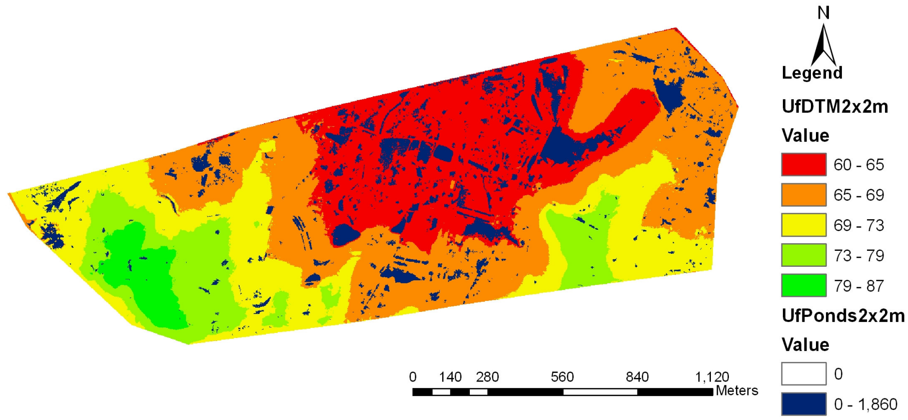


Figure 4. Spatial Distribution of Ponds Generated in 2x2m DTM resolution (Elvetham)

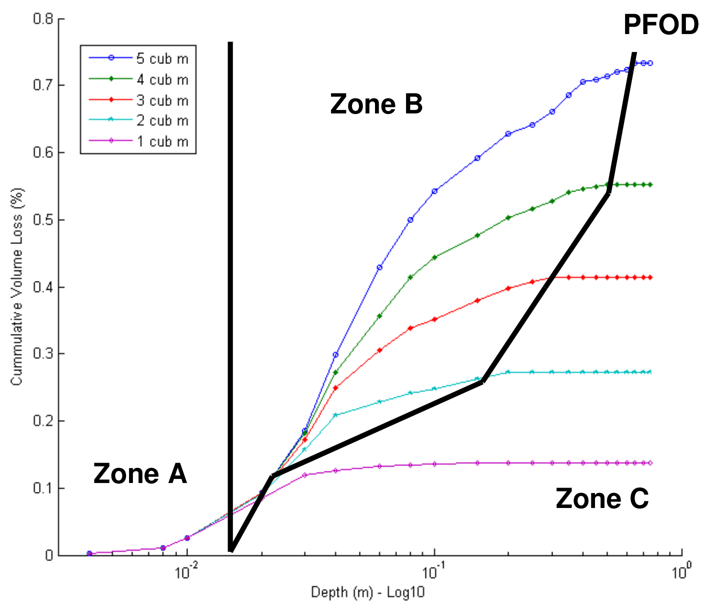


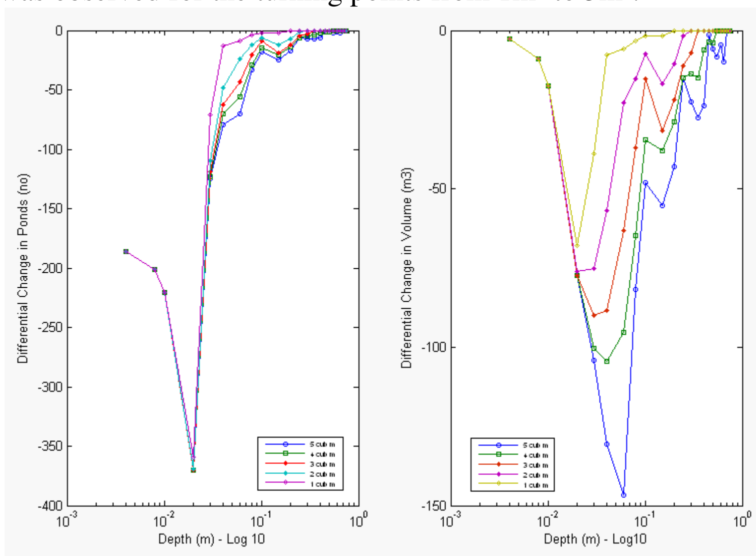
Figure 5. Cumulative Volume Loss Curve for a 2x2m DTM

From the curves generated with the Lisbon datasets, the three zones were also observed, but their lengths and sizes differ. For instance, Zone A is more pronounced in the Lisbon data sets and PFOD is hardly attained with the depths tested. This may be due to the fact that the results from the use of this tool will reflect to a large extent, terrain characteristics, which is different from place to place.

Threshold Values for Pond Filtering

From the cumulative volume-loss charts, it can be clearly determined, for each volume filter value, the PFOD, which is the point at which further increases in depths will not longer result in any further reduction in cumulative volume. However, further analysis was necessary to determine the combination of volume / depth threshold value. This was carried out bearing in mind the major goals of this exercise, which is to achieve a balance between minimisation of volume loss and elimination of noise from the DTM.

The approach adopted to carry out this analysis was to plot the differential (discrete) volume loss curves against the depth values. The result of this is as shown in Figure 6. The depth 0.02m came out as the turning point for the pond curves. On the volume curves, the turning point (depth value) for the $1m^3$ line coincide with the value from the ponds' curves and a linear increase was observed for the turning points from $1m^3$ to $5m^3$.

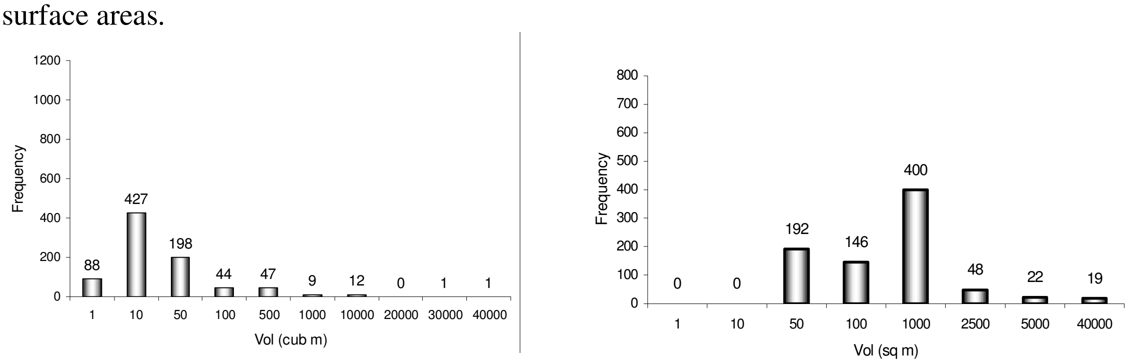


(a) (b)

Figure 6 (a,b) Differential (Discrete) changes in ponds/volume vs depths

From this, 0.02m was adopted as the threshold depth value for the 2x2m DTM. This is the inflexion point in differential ponds' curves, which also correspond to the lowest inflexion point on the differential volume curves. The threshold volume adopted was $1m^3$. Here, the volume loss is 0.112% of the total pond volume; the surface area of the ponds filtered is $473{,}040m^2$, which represents about 14.60% of the total area of the catchment.

Figure 7 shows the pond distributions for the 2x2m-filtered DTM in terms of volume and surface areas.



(a) Ponds' Volume Distribution – 2x2m DTM (Filtered)

(b) Ponds' Area Distribution – 2x2m DTM (Filtered)

Figure 7. 2x2m Smoothened DTM pond volume and area distribution before and after filtration

Flow pathways delineation

Figure 8 shows the number of pathways generated for different DTM cell sizes, without applying any filter parameters to the DTMs. The path delineation exercise for the 2x2m DTM with the selected filter parameters eventually resulted in the generation of 519 flow pathways connecting the ponds together.

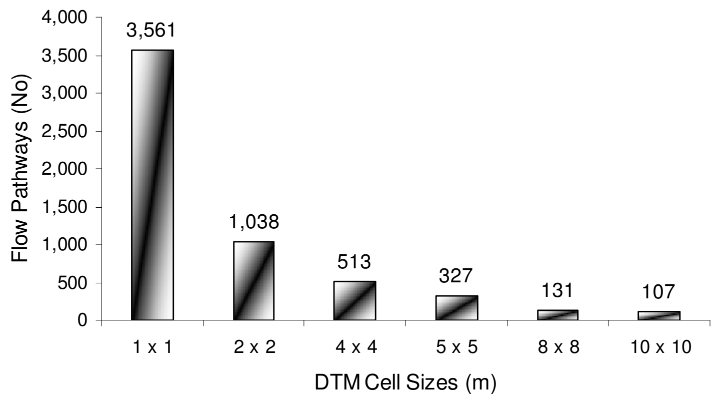


Figure 8 Number of Flow Pathways Generated vs DTM Cell Size (Smoothen Data Sets)

Figure 9 shows the paths and ponds on the study layout. This clearly shows the areas of flood vulnerability for this development.

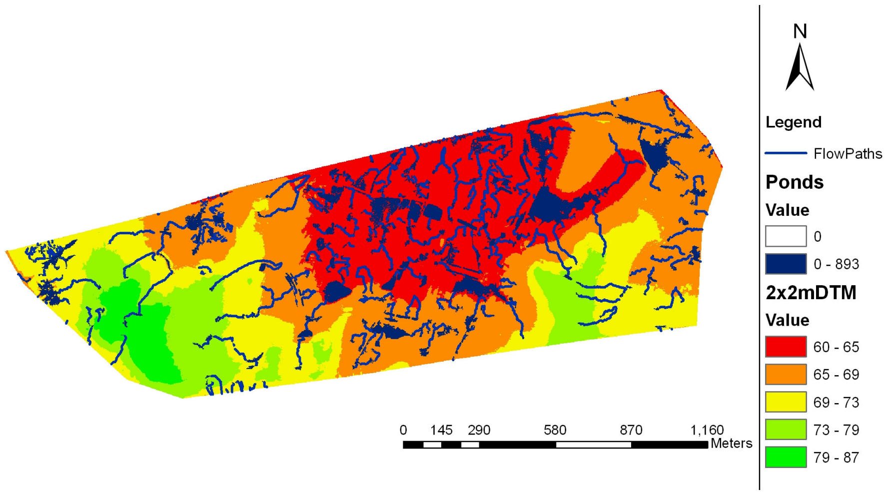
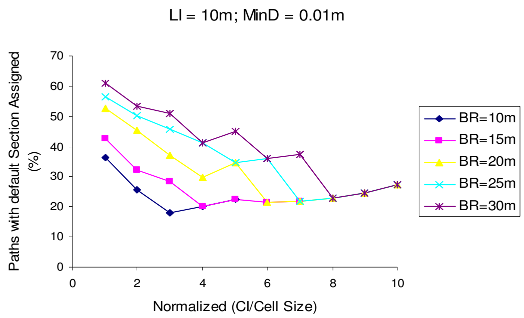


Figure 9 Spatial Distribution of Ponds and Flow Pathways for 2x2m DTM

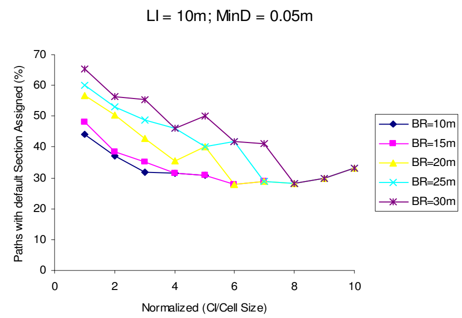
Cross Section Geometry

Sensitivity analysis was carried out on the input parameters, which are Longitudinal Interval (LI), Cross-section Interval (CI), Buffer Radius (BR), Minimum depth of flow (MinD) and Maximum depth of flow (MaxD). The objective of the exercise here is to determine the appropriate combination of the parameters such that there is a minimal number of cross section ending up with the user pre-defined sections. Multi-parameter optimization technique was deployed and the analysis was carried out in a stepwise manner, also recognising the obvious fact that the BR and CI both lie on the same axis and some kind of relationship is expected between them.

Buffer Radius: When tested against different minimum depths, the impact of BR and the different minimum depths on the number of paths assigned the default section is as shown in Figure 10. This is for a fixed LI of 10m while the CI is normalized by the DTM cell size. From figure 11, the number of paths assigned the default pathway profile is sensitive to the value of BR input parameter. This is not the expected result. It was being expected that larger values of buffer radius will give less paths assigned the default pathways because this will give the algorithm the opportunity to search for terrain related data further on the lateral axis. A look into some of the assumptions made during the development of the algorithm may explain this; otherwise, this seems inconclusive and needs to be further tested.



(a) Minimum depth of 0.01m



(b) Minimum depth of 0.05m

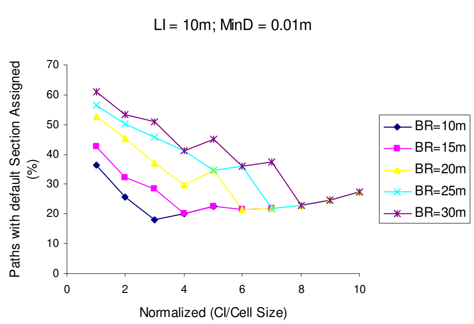
Figure 10 – Buffer Radius Sensitivity Curves for different Minimum Depths

Cross-sectional Interval: From Figures 10, it can be deduced that the number of paths assigned the default pathway profile is also sensitive to the value of the cross-section interval used for the analysis. For a given BR, the higher the CI, the lower the number of pathways assigned the default sections. Also, at a CI value of 8 times the cell size, the BR values tested gave the same result. Also, based on the findings, the cross sectional interval must be chosen such that it is less than or equal to the buffer radius (CI < BR).

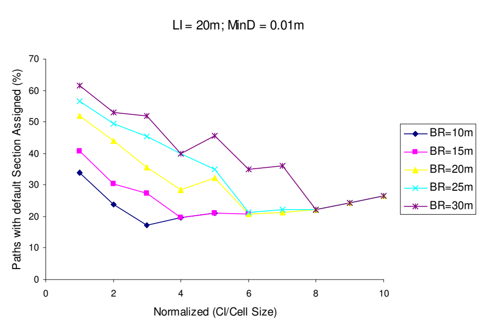
Minimum Depth: As shown in Fig 10 (a) and (b), the number of paths assigned the default pathway profile are sensitive to the Minimum depth value used for the analysis. With a given LI of 10m, it was observed that the range of the output values for various BRs with a MinD of 0.01m is 18-60%. For a MinD of 0.05m, this range is 30-65%.

Longitudinal Interval: Figure 11 (a-b) suggests that the number of paths assigned the default pathway profile is not sensitive to the value of LI. In physical terms, this will appear untrue because the shorter the distances between the cross-sections, the more details are captured to give a representation of the channel cross-section, which is close to reality. A value of 4 times the cell size also seems to be an optimum CI for this data set.

Maximum Depth: The maximum depth of flow was found not to be a sensitive parameter. However, a value of 1m is however recommended.



(a) Sensitivity of BR: LI=10m, MinD=0.01m



(b) Sensitivity of BR: LI=20m, MinD=0.01m

Figure 11 Sensitivity of Longitudinal Interval and Cross-section Interval

Summary

Based on the analysis done and the application of judgement, the following values were adopted - Longitudinal Interval – 10m; Maximum Depth – 2m; Minimum Depth – 0.01m; Cross Section Interval – 6x cell size; Buffer Radius – 20m. With these parameters, 37% of the 519 flow pathways identified were assigned the default pathway.

CONCLUSIONS

The GIS-based tool is indeed an innovation and its completion and deployment has the potential to assist in the identification of areas prone to pluvial flooding. This would be very useful to modellers and planners, especially when analysing such issues such as system performance and effects caused by new urban developments under extreme rainfall events.

The main conclusions of the sensitivity analysis research carried out in this project are as follows:

1. The DTM size adopted for analysis will affect the modelling results. There is the need to choose the right DTM cell size for analysis when using this tool.
2. Pond delineation/filtering – When filtering ponds to eliminate noise while minimising volume loss, the combination of pond depth and volume is a sensitive filtering parameter.
3. From the comparison between the results obtained from testing Elvetham and Lisbon data sets, it was clear that the Volume Loss Curves' characteristics are not standardised for different data sets. Hence, there is the need to develop appropriate charts for new datasets to be modelled with the tool.
4. Cross Section Geometry: Based on the sensitivity analysis carried out on the input parameters to generate the appropriate cross-section geometry, the following conclusions are drawn:
    a. The number of pathways generated representing the terrain features is sensitive to the input parameters of Cross-section interval (CI), minimum depth of open channels and Buffer radius. Different combinations of these are possible. The following recommendations are based on the results and analysis from this study – a value of CI between 6 and 8 times the DTM cell size and a Min Depth of 0.01m.
    b. Maximum Depth is not sensitive – a value greater than or equal to 1m is recommended.
    c. Longitudinal Interval (LI) was expected to be an important parameter, which should have been sensitive, but it appears not to be sensitive. There is the need to investigate further into this issue.
    d. Though the Buffer Radius turns out to be a sensitive parameter as expected but it exhibits a somewhat 'reversed' sensitivity. There is a need for further investigation into this as well.

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