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ABSTRACT

The newly available and more detailed and accurate elevation data sets, such as Digital Elevation Models (DEMs) generated from imagery acquired using terrestrial LiDAR (Light Detection and Ranging) and Unmanned Aerial Vehicles (UAVs), can be used to improve flood model input data and consequently increase accuracy of flood modelling results. In this paper, the impact of using off-the-shelf raster data merging tools for combining DEMs in flood modelling results is presented. Advantages of a recently developed raster data merging method are also discussed.

KEY WORDS: Data fusion; DEM merging; Overland flow modelling.

ELEVATION DATA SETS AND URBAN FLOOD MODELLING

Urban floods are one of the largest natural risks. According to Adikari and Yoshitani (2009) floods account for approximately 30% of the total losses caused by natural disasters. In order to assess risk of flooding (e.g., generate risk maps) detailed and accurate modelling results are required. The accuracy of the model results are, as in most modelling cases, strongly dependent the quality (e.g., accuracy, resolution) of the model input data. For flood models, terrain elevation plays an important role as the overland flow is mainly driven by gravity. In urban areas, fine-resolution data is of utmost importance as they encompass a large number of man-made features. This explains the need to explore new methods and solutions to generate terrain elevation data sources that (i) are easy and flexible enough to conduct frequent surveys in order to capture the changes in the catchment occupation and (ii) produce cost-effective and fine-resolution data of specific areas, such as those more prone to flooding.

Unmanned Aerial Vehicles (UAVs) make new terrain elevation data sets easy to generate (Leitão *et al.*, 2016b). They are becoming increasingly common and their application wider. UAV operation is very simple, so surveying parts of urban catchments is a cost-effective solution with the advantages of flexibility (e.g., time of the day and calendar season) and the high accuracy achieved due to the possibility of flying much lower than conventional platforms, namely, airplanes or helicopters, for acquiring such type of data. However, surveys conducted using UAVs have also some drawbacks, such as the limited battery capacity that restrict the flight duration and the maximum flight altitude – in many countries, UAVs can be operated only if they are continuously seen by the operator, which creates limitations in terms of the flight altitude as UAVs are, in many cases, small aircrafts. As such, terrain elevation data sets generated from UAV imagery, may not cover the whole area of study. This is also valid for ground-based LiDAR solutions; in urban areas, this solution is able to provide very-fine-resolution elevation data sets, but cannot survey the backyards that are behind buildings or walls.

Hence, the new available elevation data may require to be combined, i.e., merged, with existing elevation data sets to cover the whole area of interest to take advantage of the best available data sets

This paper discusses the influences on flood modelling results due to using different raster merging methods to prepare a Digital Elevation Model (DEM) that covers the whole catchment; the differences are quantified and discussed. The paper is organised as follows: the following section briefly present the raster data set merging methods. Then, the case study used to illustrate the effect of the merging methods on the flood modelling results is described. Finally, the obtained results are presented and the main conclusions of the study are summarised.

ASSESSING THE IMPACT OF DEM MERGING IN URBAN FLOOD MODELLING RESULTS

Methods for Merging Digital Elevation Models

Most Geographic Information Systems (GIS) software packages provide tools to merge raster data sets, e.g., DEMs. These raster data merging tools are known as (i) Cover type methods, (ii) Average type methods and (iii) Blend function methods (Eastman, 2012; ESRI, 2011).

Cover type methods. Cover type methods do not operate any elevation adjustment on the DEMs; DEMs are just superimposed.

Average type methods. Average type methods assign the mean elevation value within the overlapping area of the two DEMs. Hence, the elevation values within the overlapping area are changed; changing the values of the more accurate DEM.

Blend type methods. Blend type methods use a weighted average function within the overlapping area of the DEMs. As average type methods, this type of methods also change the more accurate (and detailed) DEM.

More recently, Leitão *et al.* (2016) proposed a new method, ***MBlend***

method, to merge raster data sets, which shows advantages when compared with the traditional methods available in the GIS software packages. This recently proposed method by Leitão *et al.* (2016b) preserves the accuracy of the most accurate DEM and generates smooth elevation transitions along the boundary between the two original DEMs. Figure 1 presents the flowchart of the MBLend algorithm (Leitão *et al.*, 2016b)

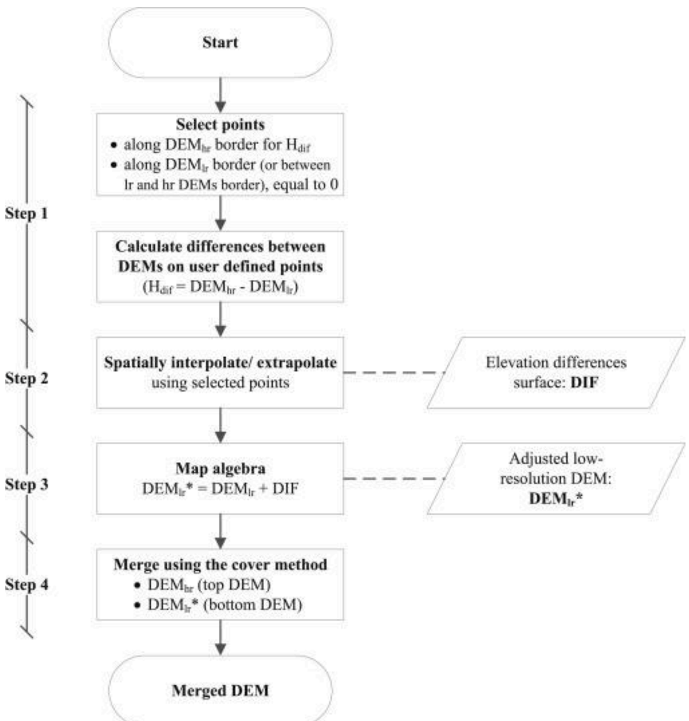

Fig. 1. Flowchart of the MBlend method proposed by Leitão *et al.* (2016b)

Flood Modelling

The CADDIES/CAFlood model (Ghimire *et al.*, 2013) was used to simulate overland flow in the catchment. It is a cellular automata based flood model that when compared with two-dimensional shallow water equation based models is substantially faster and provides similar flood modelling results (i.e., water depth and flow velocity).

Assessment of DEM Merging Methods Performance

The comparison of the overland flow modelling results focused on the analysis of the minimum, maximum, mean and standard deviation water depth values. The flood simulated time period was three hours to ensure complete runoff draining of the catchment.

CASE STUDY

Catchment Description

The catchment used to demonstrate the importance of the methods used to merge DEMs for overland flow/ flood modelling is located in Lucerne (Switzerland). Its land use is mixed (natural and urban areas) with 1.6 km^2 and is typical of a suburban Swiss catchment. The urban part of the catchment is located downstream and is much flatter than the upstream natural part.

Digital Elevation Models

To model overland flow and flooding in the catchment described above, two DEMs were available: a LiDAR DEM covering the whole catchment and a UAV DEM covering only part of the catchment area. In this specific case, the vertical accuracy of the UAV DEM was higher than the LiDAR DEM, and for that reason this latter one should also be considered when modelling urban pluvial flood risk. Although the study had included these two specific DEMs, raster elevation data sets of different sources can also be used to demonstrate the challenges of existing DEM merging methods and the advantages of MBlend. A brief description of the two DEMs used in this study is presented below.

LiDAR DEM. The LiDAR DEM was provided by the official cadastral service of the Canton of Lucerne (Switzerland). It has a spatial resolution of 0.5x0.5 m and a vertical accuracy of approximately 0.5 m. It was last updated in July 2012 (Doe, 2014) and covers the whole catchment (1.6 km^2). The minimum, maximum, average and standard deviation elevation values of the LiDAR DEM are, respectively, 434.3 m, 602.1 m, 485.9 m and 46.0 m. In terms of slope, minimum, maximum, average and standard deviation are 0%, 1127.9%, 46.0% and 126.1%, respectively.

UAV DEM. The UAV DEM was generated based on aerial photos obtained in March 2014, using a fully autonomous fixed-wing UAV (senseFly SA). The UAV is electric powered, has a wingspan of 0.96 m, and weighs approximately 0.7 kg including a payload of 0.15 kg. The UAV can cover around 0.1 km^2 in approximately two hours, which is important for the economic viability of UAV remote sensing. The photos were taken using a 16 MP compact digital Canon IXUS 127 HS camera and then processed to generate an orthophoto using the *Pix4D* software package (Strecha *et al.*, 2011). The UAV flight was conducted at approximately 114 m above ground, which enables the generation of a DEM with approximately 3.5 cm spatial resolution. Despite this maximum resolution, the UAV DEM was downsampled to the same horizontal resolution as the liDAR DEM (0.5x0.5 m). It was downsampled to match the spatial resolution of the LiDAR DEM. The vertical accuracy of the UAV DEM was estimated of approximately 2 cm. The UAV DEM covers an area of 0.35 km^2, corresponding to the urbanized part of the catchment. The minimum, maximum, average and standard deviation elevation values of the UAV DEM are, respectively, 434.3 m, 602.1 m, 485.9 m and 46.0 m. In terms of slope, minimum, maximum, average and standard deviation are 0.0%, 2885.0%, 72.7% and 185.0%, respectively.

The LiDAR and the UAV DEMs are presented in Figures 2 and 3, respectively.

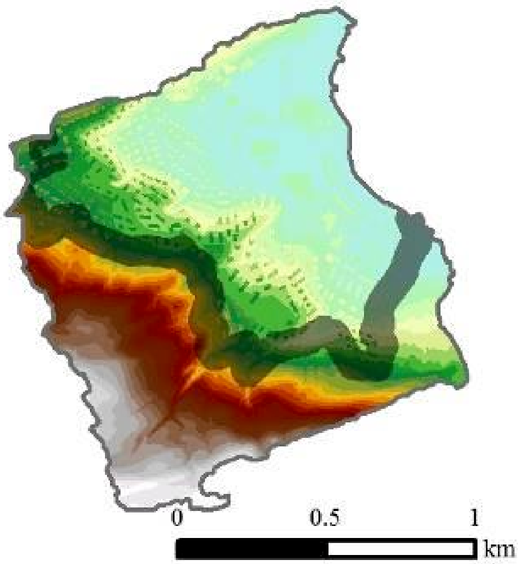

Fig. 2. LiDAR DEM used in this study (the shadowed polygon in (a) represents the area used to compare (i) the different merged DEMs and (ii) the flood modelling results)

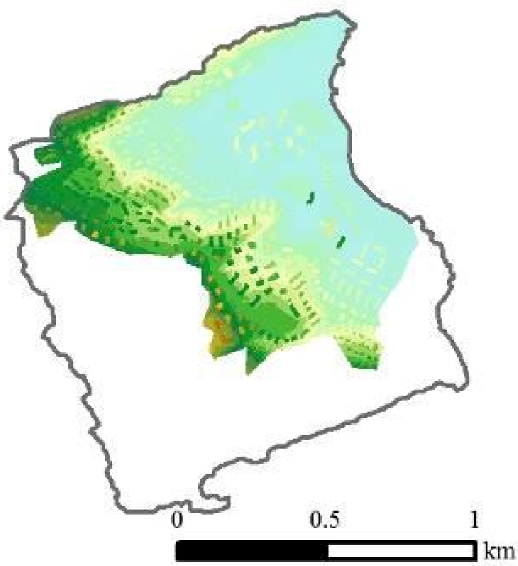

Fig. 3. UAV DEM used in this study (as shown, it does not cover the whole catchment area)

Merged DEMs. To cover the whole catchment retaining the UAV DEM information, it needed to be merged with the LiDAR DEM. This was achieved by merging the UAV DEM with the LiDAR DEM using the various raster merging methods briefly described in above. Four different DEMs were generated using the DEM merging methods described above.

Rainfall Input

A synthetic rainfall event of 10-year return period and with 60 mins duration was considered. The hyetogram was generated using the empirical relation proposed by Hörler and Rhein (1962) and the alternating block method (TxDOT, 1997). The maximum intensity of the synthetic rainfall event is approximately 120 mm h^{-1}.

RESULTS AND DISCUSSION

The elevation and slope characteristics of the merged DEMs are presented in Table 1 (only for the buffer analysis area presented in Figure 2). As can be seen from the figures presented in this table, the elevation and slope maximum, minimum, mean and standard deviations do not present substantial differences.

Table 1. Elevation and slope descriptive statistics of the DEMs used in this study calculated on a buffer area around the two DEMs boundary

DEMs	Minimum	Maximum	Mean	St. Dev.
Elevation (m)				
Cover DEM	430.7	526.9	477.3	21.2
Average DEM	430.7	526.9	477.3	21.2
Blend DEM	430.7	526.9	477.3	21.2
MBlend DEM	430.7	526.4	477.1	21.3
Slope (%)				
Cover DEM	0	2884.0	55.8	140.5
Average DEM	0	2884.0	55.7	141.1
Blend DEM	0	2884.0	55.8	140.5
MBlend DEM	0	2884.0	55.4	139.4

The water depth results obtained (within the area defined along the original DEMs boundary) using the different DEMs were different (Table 2). This was especially relevant for the results obtained using the DEM generated using the conventional merging methods (cover, mean and blend methods).

As can also be seen in Table 2, the maximum water depth obtained using the conventional DEM merging methods is smaller than that obtained using the LiDAR DEM (original DEM covering the whole area) and the MBlend DEM; this may be explained due to the fact that the artifacts created by the DEM merging conventional methods store some water, contributing thus to shallower localised water depths as less water is available to fill in the “real” terrain depressions.

Table 2. Overland flow modelling results; maximum water depth descriptive statistics obtained on a 20 m buffer area around the two DEMs

DEMs	Water depth (m)			
	Maximum	Minimum	Average	St. Dev.
LiDAR DEM	4.220	0	0.042	0.156
Cover DEM	3.858	0	0.061	0.242
Average DEM	3.858	0	0.061	0.242
Blend DEM	3.858	0	0.061	0.242
MBlend DEM	4.287	0	0.054	0.161

These results clearly highlight for the importance of DEM merging methods for overland flow models, and, in general, data fusion methods for all other types of data merging applications.

In Figures 4 and 5, the flood modelling results, maximum water depth, using the Cover and MBlend merging methods are presented. The blue colours presented the water depth: light blue represent smaller water depth while darker blue represents higher water depths. The results obtained using the Average and Blend methods are not presented as they are similar to those obtained using the Cover method.

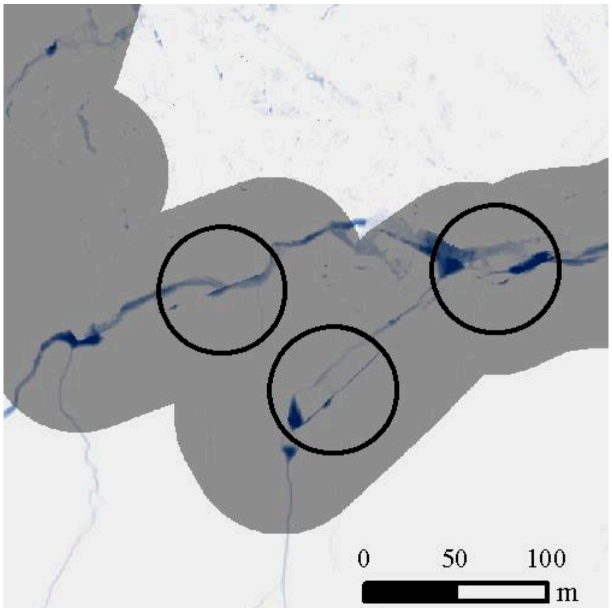

Fig. 4. Flood modelling results obtained using the cover DEM – similar results were obtained using the Average and Blend DEMs (maximum water depth in the area defined by the shadowed area defined in Figure 2; darker blue represents higher water depth values). The three highlighted areas show artifacts created by the merging method algorithm along the two DEMs boundary.

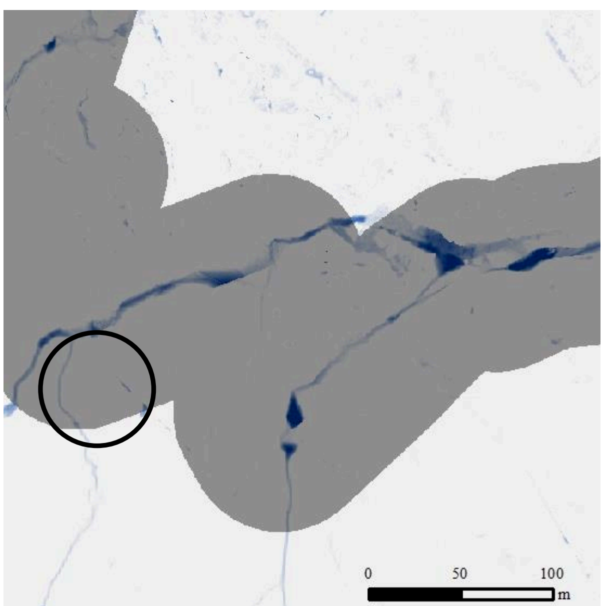

Fig. 5. Flood modelling results obtained using the MBlend DEM (max. water depth in the area defined by the shadowed area defined in Figure 2. Most of the artifacts highlighted in Figure 4 are not visible.

CONCLUSIONS

This study investigated the impact of DEM merging methods on flood modelling results. One specific objective was to evaluate best ways to incorporate newly available but incomplete terrain elevation data sets into flood modelling. The main results of this study are as follows:

- The incorporation of newly available terrain elevation data sets with existing data sets needs to be carried out prudently.
- Most of the conventional raster data set merging methods available in most of software packages do have some problems (e.g., creation of flood artifacts) when raster data sets are DEMs meant to be used for flood modelling. These problems are related essentially with the elevation differences between the two data sets, which may create surface discontinuities, contributing to flood modelling errors, e.g., erroneous water depths.
- The MBlend method proposed by Leitao *et al.* (2016b) was able to reduce the problems identified using the conventional merging methods. In contrast to the other results, no visible errors (erroneous water depth artifacts) were visible in the flood modelling results along the surroundings of the DEMs boundary in the presented case study.

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