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Towards the optimal fusion of high-resolution Digital Elevation Models for detailed urban flood assessment

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ABSTRACT

Newly available, more detailed and accurate elevation data sets, such as Digital Elevation Models (DEMs) generated on the basis of imagery from terrestrial LiDAR (Light Detection and Ranging) systems or Unmanned Aerial Vehicles (UAVs), can be used to improve flood-model input data and consequently increase the accuracy of the flood modelling results. This paper presents the first application of the *MBlend* merging method and assesses the impact of combining different DEMs on flood modelling results. It was demonstrated that different raster merging methods can have different and substantial impacts on these results. In addition to the influence associated with the method used to merge the original DEMs, the magnitude of the impact also depends on (i) the systematic horizontal and vertical differences of the DEMs, and (ii) the orientation between the DEM boundary and the terrain slope. The greater water depth and flow velocity differences between the flood modelling results obtained using the reference DEM and the merged DEMs ranged from −9.845 to 0.002 m, and from 0.003 to 0.024 m s^{-1} respectively; these differences can have a significant impact on flood hazard estimates. In most of the cases investigated in this study, the differences from the reference DEM results were smaller for the *MBlend* method than for the results of the two conventional methods. This study highlighted the importance of DEM merging when conducting flood modelling and provided hints on the best DEM merging methods to use.

1. Urban flood modelling and the need to combine different terrain elevation data sets

Floods constitute one of the greatest natural risks: Adikari and Yoshitani (2009) note that they account for approximately 30% of the total losses caused by natural disasters. Flood models are an invaluable resource for better understanding these phenomena and reducing their frequency and impact. These models can be used to understand the hydraulic behaviour of a catchment and support the design of solutions to mitigate floods, feed flood-forecasting systems so they can issue flood alerts, as well as to provide the required information to generate the flood-risk maps that are key tools for planning the territory and managing emergency responses.

The accuracy of the model results is strongly dependent on the quality (e.g. accuracy and resolution) of the input data. For the specific case of flood models, terrain elevation plays an important role, as overland flow is driven by gravity. In recent decades, Digital Elevation Models[1] (DEMs) have become the preferential source of elevation data (Wilson and Gallant, 2000; Baghdadi et al., 2005). Terrain surface features in urban areas, such as roads, curbs, buildings and other man-made features, can significantly influence the pattern of overland flow and flooding (Prodanović et al., 1994; Mark et al., 2004). For this reason, these features need to be represented in DEMs to model such phenomena. Fewtrell et al. (2008) and Leitão et al. (2009) showed the effect of DEM sources, resolution and accuracy on the delineation of overland flow paths in urban catchments and on urban flood-modelling applications. These authors concluded that for flood modelling in urban areas, the spatial resolution of the terrain representation needs to be relatively high, i.e. with a maximum raster cell size of 5 m and preferably around 1 m.

The need for high-resolution DEMs for urban flood modelling explains the interest in exploring new technologies and methodologies to generate terrain elevation data sources that (i) produce cost-effective and high-resolution data for specific areas, such as those more prone to flooding, and (ii) are easy and flexible enough to allow frequent surveys to be conducted in order to capture the changes in the catchment. Unmanned Aerial Vehicles (UAVs) and ground-based LiDAR solutions are two examples of such technologies (Leitão et al., 2016a). UAVs are becoming increasingly common and their application is broadening, thanks to their low cost and simple operation, which leads to cost-

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[1] In this study, the generic term DEM (*Digital Elevation Model*) is used to refer to the representation of terrain surfaces with no man-made features, also realised by the *Digital Terrain Model*, or of the terrain and man-made features, also realised by the *Digital Surface Model*.

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effective and flexible surveys during different times of the day and calendar seasons. However, UAV surveys also suffer some drawbacks, such as their limited battery capacity that restricts the duration and maximum altitude of flights. Terrain elevation data sets generated from UAV imagery may consequently cover only specific parts of the catchment. In urban areas, ground-based LiDAR survey solutions face a similar problem: they can provide high-resolution and high-accuracy elevation information along streets, but cannot provide data from areas located behind buildings or walls.

In any study of urban flooding, as well as in most applications for modelling earth-surface phenomena, data voids within the study area are not desirable or even possible, as they would significantly affect the modelling results. Furthermore, the use of low-resolution data because high-resolution data sets do not cover the whole area is also undesirable (Leitão et al., 2016b). The above considerations show that the available data sets must be combined[2] in order to produce one that covers the whole area of interest with the highest possible accuracy (Bourgine et al., 2004; Leitão et al., 2016b). Nevertheless, the process of merging elevation data sets from different sources with different characteristics is challenging and may be a source of elevation artefacts (Katzil and Doytsher, 2003; Luedeling et al., 2007).

According to various authors (Constantini et al., 2006; Ravanbakhsh and Fraser 2013; Leitão et al., 2016a,b), DEMs should be merged in a way that retains their highest possible accuracy while ensuring smooth transitions between the merged data sets. However, most of the conventional DEM merging methods available in GIS software (e.g. ArcGIS[3] or QGIS[4]) ignore these recommendations, and (i) change the most accurate data set in an attempt to achieve a smooth transition, or (ii) do not merge the DEMs seamlessly, creating artefacts in the representation of terrain which in turn may cause errors in the simulations of the relevant phenomena. The most common options for merging DEMs in GIS software are (i) the *cover* method, which consists of a simple overlapping of the raster data sets, and (ii) the *averaging* methods that consist in calculating the elevation mean (simple or weighted) from all DEMs on a cell by cell basis.

A few DEM merging methods have been proposed in order to resolve the problems mentioned above when merging DEMs, and also as a result of the newly available elevation data sources. Papasaika et al. (2008, 2009), Schindler et al. (2011), Huafei et al. (2012) and Fuss et al. (2016) have all presented methods that aim to take advantage of multiple data sets covering exactly the same area and thus increase the accuracy of the elevation representation in the merged DEM. However, they do not resolve cases in which different DEMs overlap only partially without the same coverage. In order to address this latter case, other authors, e.g. Constantini et al. (2006); Warriner and Mandlburger (2005); Leitão et al. (2016b) and Petrasova et al. (2017), have proposed different DEM merging methods that minimise the effects of the horizontal and vertical differences between the original DEMs, hence removing the abrupt transitions between them, while also taking advantage of the best and most accurate DEM.

An example of this latter type of DEM merging method, the *MBlend* method, was proposed by Leitão et al. (2016a,b). It combines DEMs retaining the elevation values of the most accurate and higher resolution DEM while achieving a smooth transition between the two DEMs. Along with two conventional DEM merging methods commonly available in GIS software, the *Cover* and the *Average* methods available in the ArcGIS "Mosaicking" tool, the *MBlend* method[5] is used in this study to evaluate the potential impact of DEM merging on urban flood-modelling results. In addition, the present study aims to:

- Demonstrate the problems created by conventional DEM merging methods (e.g. *cover* and *average* methods) when used to conduct urban surface flow and flooding simulations, and
- Evaluate their performance and show the advantages of the *MBlend* method for merging DEMs in urban surface flow and flooding simulations, as its first application.

2. Methodology

2.1. Study area and DEMs used in this study

The current study involves three DEM merging situations and three different merging methods which are used to generate DEMs subsequently used for flood modelling in order to analyse the impact of DEM merging on flood hazard assessment. A total of ten flood simulations were conducted: nine of them using merged DEMs plus one using a reference DEM (the DEM_{UAV}).

The study is performed in part of a semi-urban catchment located in Switzerland, 0.9 km^2 in area. The downstream part of the study area is relatively flat. The DEMs used were selected from two original ones obtained using two different technologies: airborne LiDAR and UAV photogrammetry. Both these technologies produce high-resolution DEMs and are, according to Leitão et al., (2016b), suitable for overland flow and flood modelling in urban areas.

2.1.1. LiDAR DEM

The LiDAR DEM used in this study was provided by the official cadastral service of the Canton of Lucerne (Switzerland): it is presented in Fig. 1a. It has a spatial resolution of 0.5 $\times$ 0.5 m and a vertical accuracy of approximately 0.5 m. It was last updated in July 2012 (Doe, 2014). The minimum, maximum, average and standard deviation elevation values from the LiDAR DEM are 434.3, 602.1, 485.9 and 46.0 m respectively.

2.1.2. Original UAV DEM

The original UAV DEM (DEM_{UAV}), presented in Fig. 1b and used as the reference DEM in the analysis, was generated from aerial photos obtained in March 2014 using a fully autonomous fixed-wing UAV[6]. This UAV is electrically powered, has a wingspan of 0.96 m and weighs approximately 0.7 kg, including a payload of 0.15 kg. It 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 114 m above ground, which enables a DEM with approximately 0.035 m spatial resolution to be generated. Despite this maximum resolution, the DEM_{UAV} was downsampled to match the horizontal resolution of the LiDAR DEM (0.5 $\times$ 0.5 m). The vertical accuracy of the DEM_{UAV} was estimated to be approximately 0.02 m. The minimum, maximum, average and standard deviation elevation values from the DEM_{UAV} are 434.3, 602.1, 485.9 and 46.0 m respectively.

The elevation differences between the two original DEMs are presented in Fig. 1c. As can be seen, there is a small overall bias between the two DEMs, as the elevation differences are not zero meters in most of the area. This bias is an interesting feature for the current study, as it allows different DEM merging cases to be investigated, as presented in the following two sections. Despite this bias, elevation differences occur randomly over the study area.

[2] In the literature, methods of combining different raster data sets also refer to "*Fusion*", "*Merging*" or "*Mosaicking*". In this study, the authors adopt the term "*Merging*" for methods that combine multiple raster data sets, e.g. DEMs.

[3] ArcGIS is a widely used commercial GIS software: http://www.arcgis.com3

[4] QGIS is a widely used free and open-source GIS software: http://www.qgis.org4

[5] The r.mblend tool is freely available within the GRASS GIS software: https://grass.osgeo.org/grass72/manuals/addons/r.mblend.html5

[6] eBee: SenseFly SA