Improving merge methods for grid-based digital elevation models

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Abstract

Digital Elevation Models (DEMs) are used to represent the terrain in applications such as, for example, overland flow modelling or viewshed analysis. DEMs generated from digitising contour lines or obtained by LiDAR or satellite data are now widely available. However, in some cases, the area of study is covered by more than one of the available elevation data sets. In these cases the relevant DEMs may need to be merged. The merged DEM must retain the most accurate elevation information available while generating consistent slopes and aspects. In this paper we present a thorough analysis of three conventional grid-based DEM merging methods that are available in commercial GIS software. These methods are evaluated for their applicability in merging DEMs and, based on evaluation results, a method for improving the merging of grid-based DEMs is proposed. DEMs generated by the proposed method, called `MBlend`, showed significant improvements when compared to DEMs produced by the three conventional methods in terms of elevation, slope and aspect accuracy, ensuring also smooth elevation transitions between the original DEMs. The results produced by the improved method are highly relevant different applications in terrain analysis, e.g., visibility, or spotting irregularities in landforms and for modelling terrain phenomena, such as overland flow.

Keywords: Data merging, Digital Elevation Models, Grid-based rasters, Terrain analysis.

1. Introduction

1.1 General

Terrain Elevation Models such as TIN (Triangulated Irregular Network) and grid-based formats, e.g., DEMs (Digital Elevation Models), are the primary sources of elevation data used for the majority of rainfall-runoff modelling, as well as other terrain surface-influenced phenomena (Saunders, 1999; Wilson and Gallant, 2000; Baghdadi *et al.*, 2005). The resolution and accuracy of these data sources are of the utmost importance in modelling land-driven processes. As an example, the study of surface runoff cannot be conducted when parts of the catchment area are excluded due to lack of high-resolution DEMs (Leitão, 2009). It is also not recommended to use a low-resolution DEM dataset for the whole catchment area when parts of the area are covered by high-resolution and high-accuracy DEMS.

In recent years, a new range of Digital Elevation Model acquisition technologies have become available; these include airborne and ground-based LiDAR (Light Detection and Ranging) and aerial photogrammetry based on images captured by Unmanned Aerial Vehicles (UAVs) (Künge *et al.*, 2011; Moy de Vitry, 2014). The solution suggested here is therefore to merge the most accurate of all available DEM sources in order to produce a single DEM that covers the whole area of interest with the highest possible resolution and accuracy. The high number of man-made features and rapid changes in elevation (buildings, embankments, urban features, etc.) (Ghimire *et al.*, in press) require detailed representation of terrain in urban and floodplain areas

Through the process of merging DEMs, it is possible to generate DEMs that cover larger areas or refine existing DEMs after up-to-date surveys are conducted (Ruiz *et al.*, 2011). Problems arise when DEMs are combined with, for example, sewer manhole surveying data, or when an old DEM of the whole catchment is to be merged with patches of updated LiDAR or OrthoPhoto data of streets and other fabric features. DEMs generated by different acquisition and interpolation techniques may have different characteristics; these may include spatial resolution, accuracy, geographic coordinate system, and acquisition dates. As a result, for the same location on the xy-domain of the terrain, two or more elevation values may be available depending on the dataset considered. Although these elevation differences (or inconsistencies) might be within the threshold for that particular elevation data set, due to their nature they can produce unrealistic and inconsistent terrain slope and aspect along the DEMs' borders (Katzil and Doytsher, 2003). Simple DEM merging methods may increase these inconsistencies (Luedeling *et al.*, 2007), and this may, in turn, produce incorrect modelling results such as, for example, unrealistic surface flow patterns resulting in unrealistic surface runoff modelling results. Therefore, there is a need for novel methods that can generate complete and accurate DEMs. Such methods must be able to extract all and only the correct data from different elevation data sets (Ravanbakhsh and Fraser, 2013). Such methods must retain the key features of the most accurate DEMs, placing particular emphasis on the boundary areas between the different DEMs.

With several data sources available, the aim of merging DEMs is to combine one or more elevation data sources such that each area is represented by a combination of the most accurate sources available (Bourgine, 2004).

1.2. Conventional DEM merging methods

Commercial Geographic Information Systems (GIS) software provide functions for merging two or more grid-based (raster) data sets. These methods assume that grid-based DEMs have the same spatial resolution (cell size), and also the same coordinate system. The conventional methods to merge DEMs are: (i) `Cover` type methods, (ii) `Average` type methods and (iii) `Blend` function methods (Eastman, 2012; ESRI, 2011).

`Cover` type methods do not operate any elevation adjustment on the DEMs; DEMs are just superimposed. The DEM resulting from this spatial operation has cell values equal to the top DEM in the area represented by this DEM; in the remaining area the cell values are equal to the values of the bottom DEM. The choice of which DEM is the top DEM is made by the user, but in order to take advantage of the most accurate elevation data available, a high-resolution DEM (DEM_{hr}) is preferred. The main issue is that the resulting DEM may have significant elevation discontinuities (cliffs) along the boundary between the DEMs, and this creates erroneous slope and aspect values (Hickey, 2000).

In the `Average` and `Blend` methods, elevation adjustments are performed within the overlapping area of the DEMs being merged. `Average` methods assign the average value of the elevation within the overlapping area of the two DEMs. Hence, only the elevation values within the overlapping area are changed. Usually, the simple average is considered (Eq. 1).

$$z_{adjusted(i,j)} = \frac{z_{hr(i,j)} + z_{lr(i,j)}}{2}, \tag{1}$$

where $z_{hr(i,j)}$ is the value of the cell whose centre point has xy coordinates in the high-resolution DEM (DEM_{hr}), $z_{hr(i,j)}$ is the value of the cell whose centre point has xy coordinates in the low-resolution DEM (DEM_{lr}) and $z_{adjusted(i,j)}$ is the value of the cell whose centre point has xy coordinates in the output raster.

There are, however, averaging methods that consider weighted averages; this is the case for the Mosaic tool available in the IDRISI software (Eastman, 2012). In an attempt to resolve the issue of elevation discontinuities reported in the case of the `Cover` DEM merging methods, `Average` DEM merging methods create a smooth transition between DEMs. However, due to the adjustment of the elevation values within the overlapping area, the elevation values of the high-resolution DEM are changed, and consequently the high accuracy of the elevation values is lost.

`Blend` methods use a weighted average function within the overlapping area of the DEMs. Outside the overlapped area, the cell values on the output raster are the same as the ones that appear on the input DEMs. The `Blend` function curve can be linear, smoothed (for example, bicubic), or discontinuous. In the particular case of ArcGIS software (ESRI, 2011), the function implemented is based on the work developed by Franke (1982). The proximity analysis equation applied to calculate cell values within the overlapping area is called the Cubic Hermite (Eq. 2).

$$W_{(i,j)} = 1 - 3s_{(i,j)}^2 + 3s_{(i,j)}^3, \tag{2}$$

where $W_{(i,j)}$ is the weight factor and s*(i,j)* is the normalised distance of the width of the overlapping area (values ranging from 0 to 1). The distance *s* is normalised by the distance between the boundaries of the overlapping area. The new elevation values within the overlapping area are calculated according to Eq. 3.

$$z_{adjusted(i,j)} = z_{hr(i,j)} \times W_{(i,j)} + z_{hr(i,j)} \times \left(1 - W_{(i,j)}\right) \tag{3}$$

where $z_{hr(i,j)}$ is the value of the cell whose centre point has xy coordinates in the high-resolution DEM (DEM_{hr}), $z_{hr(i,j)}$ is the value of the cell whose centre point has xy coordinates in the low-resolution DEM (DEM_{lr}), $z_{adjusted(i,j)}$ is the value of the cell whose centre point has xy coordinates in the output raster and the weight factor $W_{(i,j)}$ is calculated using Eq. 2, for example.

Like the `Average` methods, `Blend` methods also change the elevation of DEMs within the overlapping area, reducing the accuracy of the high-resolution DEM and increasing the uncertainty in elevation, slope and aspect of the resulting DEM.

Damron (2002) presented an approach to merge LiDAR and IFSAR (InterFerometric Synthetic Aperture Radar) DEMs that is based on DEMs reliability as described in metadata (i.e. DEMs information about Datum/Geoid, coordinate system, etc.). The author concluded that these metadata are highly relevant when merging DEMs when analysing the accuracy of the DEM merging process. The methodology Damron (2002) used to merge DEMs is the ArcINFO Grid insert, which can be classified as a `Cover` type method.

Another type of DEM merging method was presented by Warriner and Mandlburger (2005); this method aims to achieve a smooth transition from one DEM to another by adjusting the elevation values of both DEMs within a certain tolerance band. This results in a weighted average in which the weights depend on the distance from the centre of the tolerance band. This method is similar to the general `Blend` method, with the advantage that only the elevation values within the tolerance band are modified. In this way, the extent of changes can be limited and controlled by the user when defining the boundary width. On the downside, the width of the band, which influences the number and magnitude of elevation changes and therefore has an important effect on the resulting merged DEM, needs to be defined manually. Unfortunately, Warriner and Mandlburger (2005) did not suggest an approach to automatically define the tolerance band.

1.3. Drawbacks and challenges of conventional methods

`Cover` methods generate terrain surface discontinuities (abrupt elevation changes) on the merged DEMs along the original DEMs' boundaries. These discontinuities, which are created due to the elevation differences between the high and low-resolution DEMs, are smoothed in the case of the `Blend` method. The `Average` and `Blend` methods also change the high-resolution DEM elevation in order to smooth the elevation differences between the two original DEMs. This can be seen as a disadvantage of these methods, as it means that they do not take full advantage of the most accurate available elevation data.

The drawbacks identified in the commercially-available DEM merging methods in this section demonstrate the need for improving DEM merging methodologies. A new method that retains the high-accuracy DEM data while creating smooth transitions between the two original DEMs is presented in this paper, based on the concept that this can be achieved by modifying *only* the low-resolution DEM data. The proposed method is actually similar to the Warriner and Mandlburger (2005) method, but with a non-symmetric and auto-adjusted tolerance band. The results obtained using the new method are compared with results obtained using the three conventional DEM merging methods.

2. An improved DEM merging method: the Modified Blend (`MBlend`) method

2.1. Rationale

A method to merge two DEMs while preserving the accuracy of the most accurate DEM is presented in this paper and is called the Modified Blend (`MBlend`) method. `MBlend` assumes that the two original DEMs have the same spatial resolution (i.e. same cell size), a common geographic coordinate system and associated projection, and similar mean elevation within the overlapping area.

If the first two criteria are not met it is necessary and preferable to adjust the lower resolution and accuracy DEM so that they match the specifications of the DEM with highest resolution (the coordinate system can be any as long as it is the same in the two DEMs). Functions such as spatial resampling, geo-referencing and wrapping are available in most commercial GIS software, and can be used to perform the adjustments mentioned above. The third criterion is an attempt to match the elevation values of the two DEMs.

If the average heights of the two DEMs within the overlapping area are different, the height of the DEMs should be adjusted so that their average elevation for the same area is similar. The selection of which DEM should be used as the reference DEM depends on metadata and known data reliability.

2.2. Methodology

`MBlend` generates a grid-based surface by using the elevation differences calculated between the two DEMs at automatically generated user-specified points within the overlapping area – this grid-based surface is called DIF. This surface is then used to adjust the elevation of the low-resolution DEM (DEM_{lr}) and thereby obtain a smooth elevation transition between the two DEMs. The number of points used to generate the DIF surface could be one point for each cell that falls on the boundary of the common xy-area within the two DEMs. The experience gained during the development of the method indicates that one point per boundary cell (i.e. the maximum number of candidate points) produces more accurate merged DEMs. In general, the more points used to generate a DIF surface, the more detailed and accurate the results.

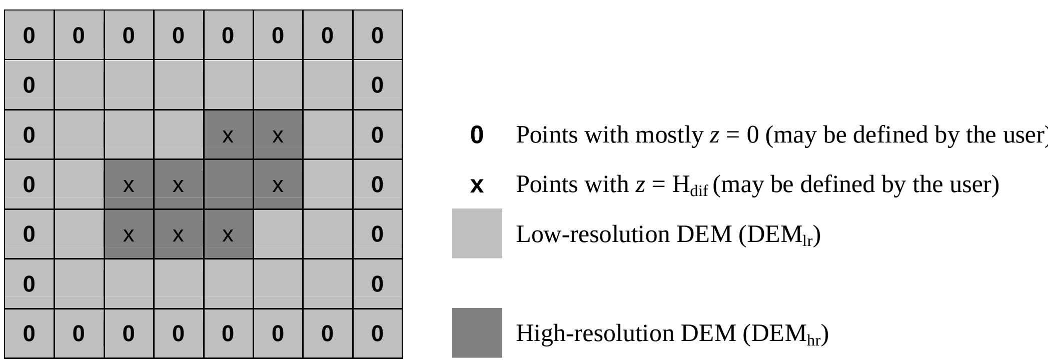


Figure 1. Possible location of points used to generate the DIF surface (interpolation points)

In the second step, selected points along the common boundary of the two DEMs (marked with **x** on Figure 1) are used as elevation difference source points to generate the DIF using spatial interpolation methods. For example, the Inverse Distance Weighted (IDW) method (Shepard, 1968), the Kriging method (Krige (1951), cited in Soares, 2000) or splines could be used. It is known that some interpolation techniques oscillate around the sample points, i.e., inexact interpolation techniques (Burrough and McDonnell, 1998), and thus may create unexpected results in the DIF surface. Such oscillations can be avoided via linear interpolation methods. An extra set of points located along the DEM_{lr} border only (i.e. not located along the overlapping area boundary between the two DEMs) is required to create the DIF (marked with **O** on Figure 1). The values assigned to these points should be zero, i.e. zero elevation difference. In order to limit the extent of the changes on the DEM_{lr}, the zero points should be moved from the edge of the DEM_{lr} towards the edge of the area of elevation adjustments. It is possible to automatically generate zero points using distance GIS functions in which the distance can be either from the DEM_{lr} border or from the DEM_{hr} border to the DEM_{lr} border.

The third step consists of adding the DIF surface representing the elevation differences to the low-resolution DEM in order to create an updated low-resolution, DEM_{lr^*} (Eq. 4).

$$z_{lr^*(i,j)} = z_{lr(i,j)} + z_{DIF(i,j)}, \quad (4)$$

The fourth and final step is to merge the high-resolution DEM and the updated low-resolution DEM (DEM_{lr}^*) using the `Cover` conventional DEM merging method, with the high-resolution DEM set to be the top DEM. Figure 2 presents a flowchart describing the steps of `MBlend`.

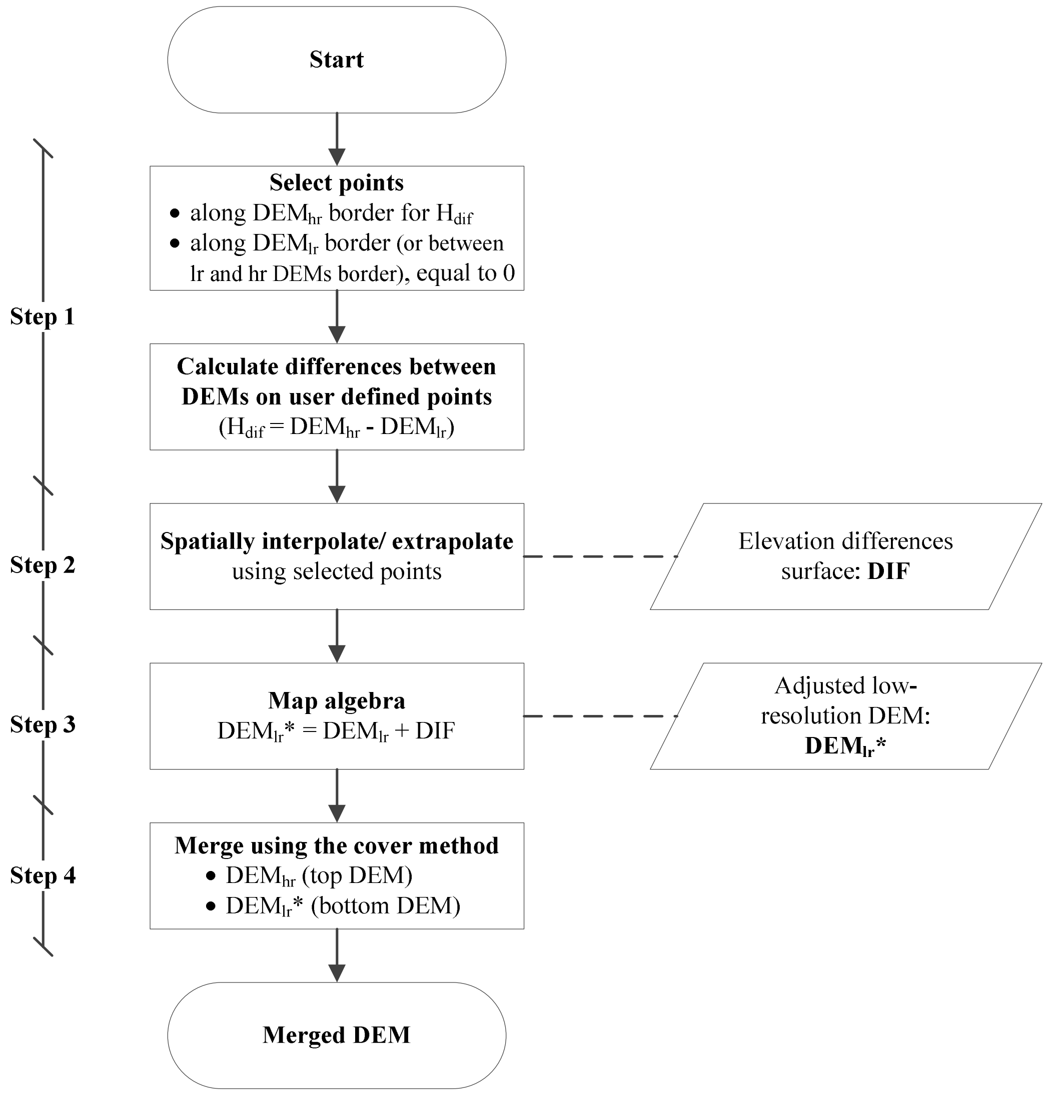


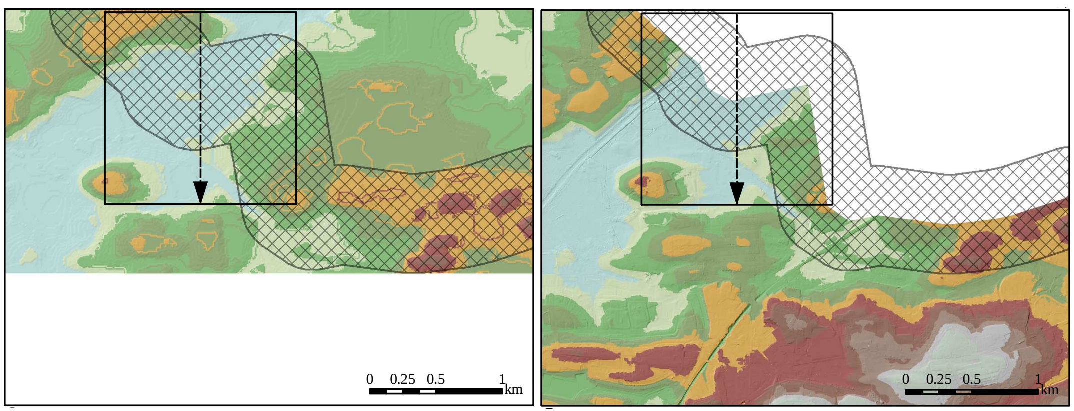
Figure 2. Flowchart of `MBlend`

`MBlend` has significant advantages when compared to the conventional DEM merging methods. With `MBlend` the band width where elevation changes occur does not have to be defined *a priori*, as in the algorithm described by Warriner and Mandlburger (2005). Using a selected interpolation algorithm, the cell values of the DIF surface are automatically interpolated based on the elevation differences between the two DEMs, and the user can control the extent of the influenced area. The two key advantages of this method are (i) the elevation changes are performed only in the less accurate DEM, the elevation accuracy of the high-resolution DEM is retained, and (ii) a smooth transition between the two DEMs is achieved. The proposed method is simple to implement and can be easily performed using standard functions found in most commercial GIS software.

3. Test areas and data sets

3.1 General

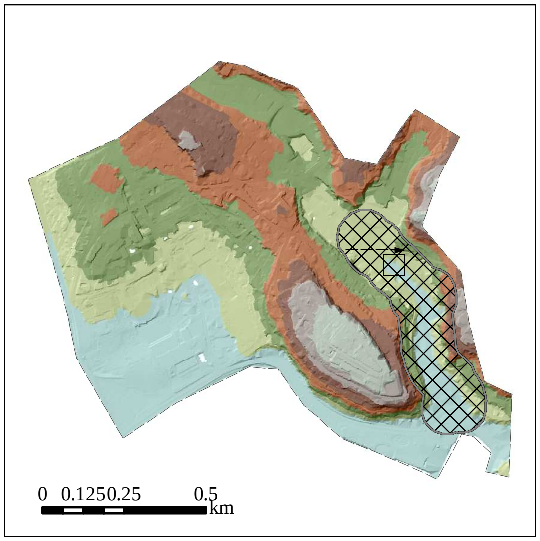
Two areas in the UK were used to compare the results obtained from `MBlend` with those obtained from the three conventional methods. The first area, Study Area 1, is located in Bishopbriggs (near Glasgow) and covers approximately 3.5 km^2. The elevation ranges between 44 and 104 m with an average value of 66.9 m. Two DEM data sets were available for this area; one generated using the contours and height spots (cartographic DEM, Figure 3a) and the second generated using airborne LiDAR technology (LiDAR DEM, Figure 3b).



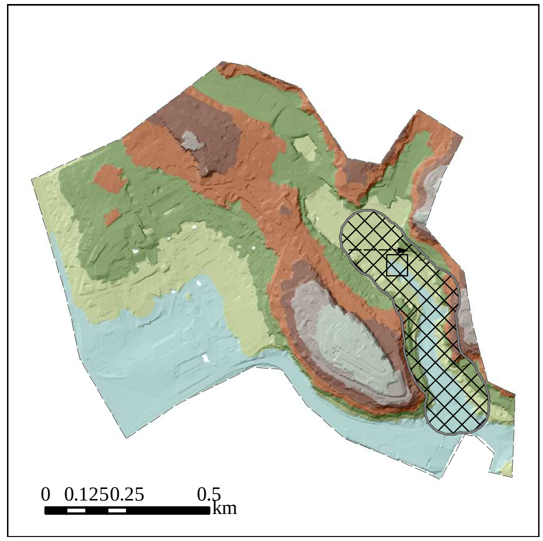
(a) low-resolution DEM (cartographic) (b) high-resolution DEM (airborne LiDAR)

Figure 3. Study Area 1 DEMs. The solid line bounded square, 1,450x1,450 pixel, and the dashed line will be used in Figure 5, which presents the results of the merging methods and the elevation profiles; the meshed area will be used in the evaluation of the slope and aspect differences between the original and merged DEMs

The second area, Study Area 2, is located in Torquay (south west of England); this area is significantly smaller (1.1 km^2) than Study Area 1, and is a densely urbanised area, occupied by buildings and streets. Terrain elevation varies significantly from sea level up to about 70 m, with an average elevation of 24.5 m. In this area, the available DEMs were obtained using airborne and ground-based LiDAR (Figure 4).



(a) low-resolution DEM (airborne LiDAR)



(b) high-resolution DEM (ground-based LiDAR)

Figure 4. Study Area 2 DEMs. The solid line bounded square and the dashed line will be used in Figure 6, which presents the results of the merging methods and the elevation profiles; the meshed area will be used in the evaluation of the slope and aspect differences between the original and merged DEMs

3.2. Cartographic (contour) DEM

Ordnance Survey (OS) cartographic elevation data for Study Area 1 were provided by the Department for Environment, Food and Rural Affairs (DEFRA, UK). These data were provided in the NTF Level 5 ASCII format, which consists of a set of points (eastings, Xx; northings, Yy) with height (Zz) values associated. For the cartographic DEM the data was provided in two square data blocks where the dimension of each block is 5,000 m and each block contains 250,000 points evenly spatially distributed. These two blocks, identified as blocks 57 and 67, containing in total 500,000 elevation points, were then used to generate the cartographic DEM. These two blocks do not cover the whole of Study Area 1 catchment; they cover areas outside the catchment boundary, and thus were cropped to the Study Area 1 catchment parts only. To generate the DEM (4,000 rows x 2,000 columns), the data were first converted to the ESRI point shapefile format, and then interpolated. Although the cell size of the cartographic DEM is 1x1 m, its horizontal accuracy is not better than 10 m because the distance between the elevation source points of the OS data used to generate the DEM was 10 m; the achieved vertical accuracy is ±1 m.

3.3. Airborne LiDAR DEMs

Both LiDAR data sets used in this study were acquired using the Optech ALTM 2033 laser scanner. The spatial resolution of the LiDAR data is 1 m (cell size of 1x1 m) with vertical accuracy of ±0.15 m (Petr *et al.*, 2008). The DEM of Study Area 1 (4,000 rows x 3,000 columns) covers only 70% (approx. 8.4 km^2) whereas the DEM of Study Area 2 (1,477 rows x 1,274 columns) covers 100% of the study area (approx. 1.1 km^2)

3.4. Ground-based LiDAR DEM

The elevation data used to generate the ground-based LiDAR DEM (300 rows x 535 columns) was acquired using the Optech LYNX Mobile Mapper technology provided by the UK Environment Agency. This consists of a vehicle-based LiDAR system with two LiDAR units mounted on the roof of the vehicle. It also has two Global Positioning Systems (GPS) receivers to accurately position the vehicle. This technology can record up to 200,000 measurements of the surrounding environment per second, with a vertical accuracy of approximately 0.05 m in good operational conditions (Kaartinen *et al.*, 2012) and is currently one of the best technologies available to generate high-quality, detailed DEMs. However, although high-quality DEMs are generated by this technology, in urban areas it can only capture the elevation in a strip along the streets (maximum 200 m either side of the vehicle). The UK Environment Agency survey was carried out in August 2008 along Union Street and Fleet Street (Figure 4b).

For the study reported here, 1 m horizontal resolution DEM has been used. Although the data have been grouped to generate the 1 m DEM grid, these data have a significantly higher level of detail and accuracy than the (more conventional) 1 m resolution airborne LiDAR data.

4. Results and discussion

4.1. Evaluation

The results obtained by the DEM merging methods were compared in terms of changes in the elevation values of the original DEMs. The changes were also measured by analysing the elevation profile across the boundary between the two DEMs, by assessing the elevation differences between the merged DEMs and by examining the changes in slope and aspect.

4.2. Study Area 1 results

The elevation difference between the two DEMs within the overlapping area shows an almost random Gaussian distribution with a mean elevation difference of 1.0 m and a standard deviation of 2.6 m, which is similar to the vertical accuracy of the contour DEM, i.e. ±1 m (Figure 5).

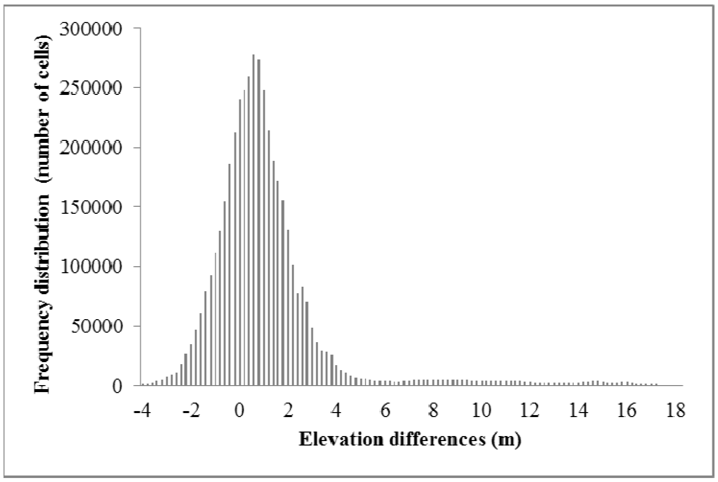


Figure 5. Elevation differences between DEM_{hr} and DEM_{lr} (Study Area 1)

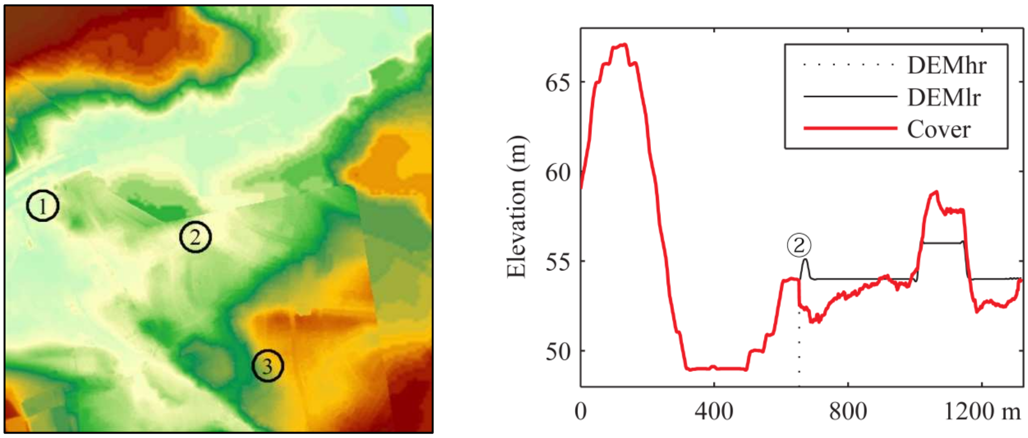
From Figure 5 it can be seen that the maximum elevation difference between the two DEMs is quite large and is close to 17.6 m.. This difference occurs only in one localised area (approx. 0.2 km^2), which was visually analysed using aerial images taken between 2002 and 2012 (Google Earth, 2002; 2005; 2006; 2009; 2011; 2012). Based on this analysis that consisted in the comparison of the different images available in Google Earth, it was found that in this specific area, the DEM_{lr} represents the terrain more accurately, as no construction was visible in the images in this area that would explain the elevation differences between the two DEMs and between this area and its surroundings; the 17.6 m elevation difference probably results from LiDAR detection or processing problems, which are not reported in the LIDAR DEM metadata.

Terrain continuity comparison

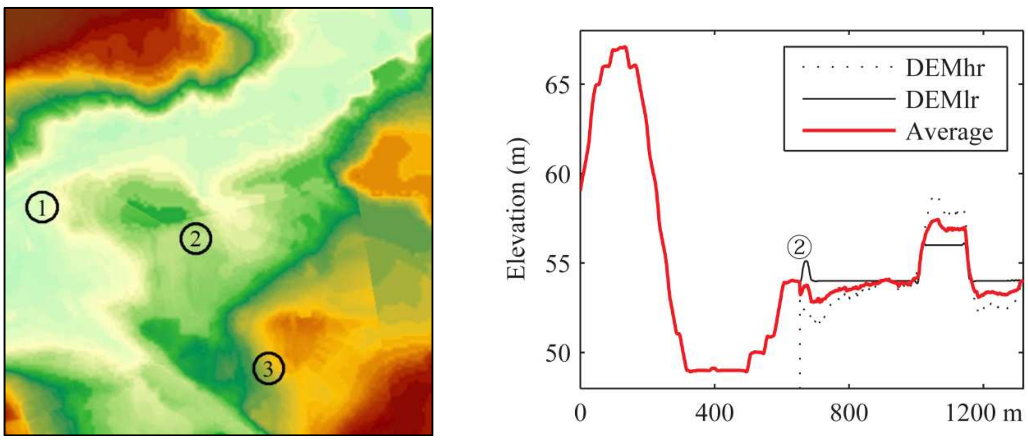
The results obtained using the four DEM merging methods show noticeable differences, as revealed by a close inspection of Figure 6. The elevation profiles show that there are some differences among the merged DEMs, and between the merged DEMs and the original DEMs. The main differences between the merged and the original DEMs can be found close to the DEMs boundary, which occurs at around 650 m on the horizontal axis of the elevation profiles presented in Figure 6).

The `Cover` method (Figure 6a) did not perform elevation changes in any of the original DEM_{lr} or DEM_{hr}. For this reason, the results obtained by this method showed an abrupt terrain discontinuity between the areas represented by the DEM_{hr} and DEM_{lr} (see ② in Figure 6a). The `Average` method performed changes within the overlapping area. The details visible in the area represented by the DEM_{hr} are lost (see ① in Figure 6b) as the high accuracy elevation of DEM_{hr} (see ③ in Figure 6b). Despite the changes performed, the DEM obtained using this method still shows a terrain discontinuity along the boundary between the two DEMs (see ② in Figure 6b). Figure 6c shows the results obtained by using the `Blend` DEM merging method. This method also performed changes within the overlapping area; however, when the DEM obtained using this method is compared with that obtained using the `Average` method it is clear that the loss of detail is significantly smaller (see ① and ③ in Figure 6c). The transition achieved between the two DEMs is generally smooth; however, at location ④ of Figure 6c, abrupt terrain discontinuities are still noticeable.

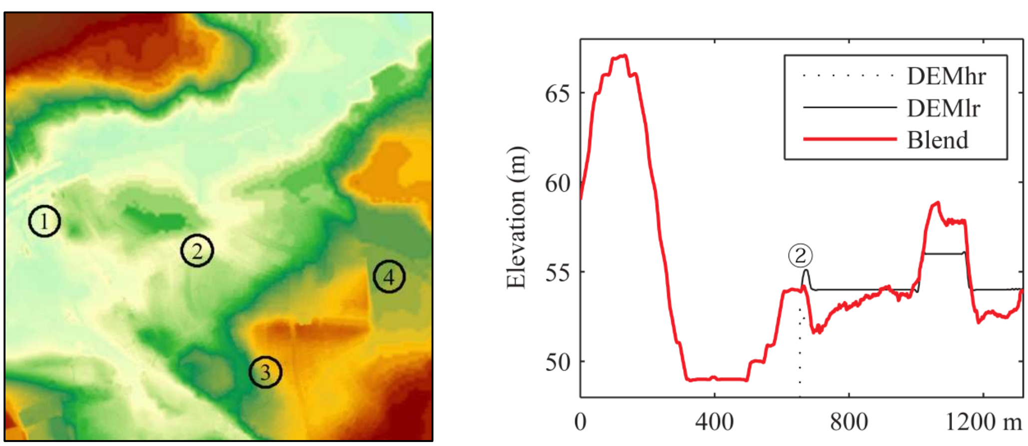
Unlike the two previous methods, `MBlend` only adjusts the elevation values of the DEM_{lr} cells. It creates a smooth transition between the two DEMs while retaining the details and accuracy level of the DEM_{hr} (see ① and ③ in Figure 6d). These two characteristics could not be achieved by using conventional DEM merging methods. The area where the changes occur is determined by the DIF interpolated surface (see Figure 7) created during the methodology process, which in turn is influenced by the elevation differences between the two DEMs, and by the interpolation method used.



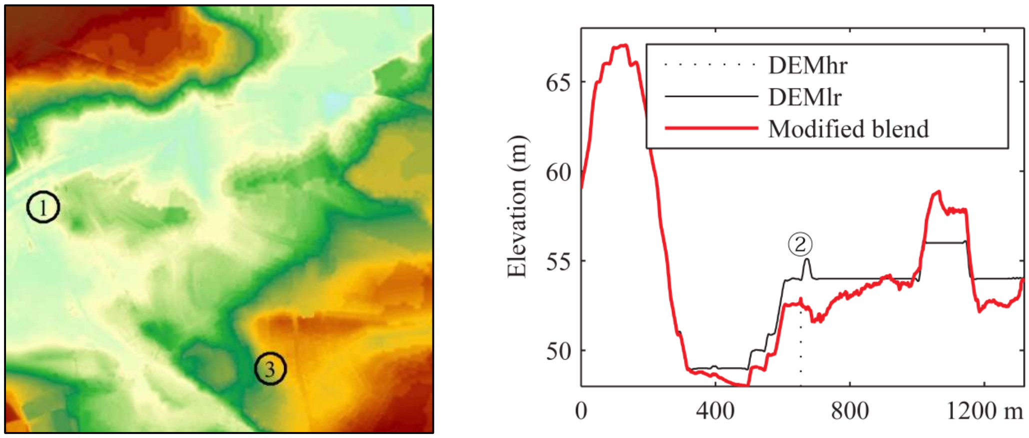
(a) `Cover` method



(b) `Average` method



(c) `Blend` method



(d) `MBlend`

Figure 6. Results of DEM merging – DEMs boundary occurs at around 650 m on the horizontal axis of the elevation profiles (Study Area 1)

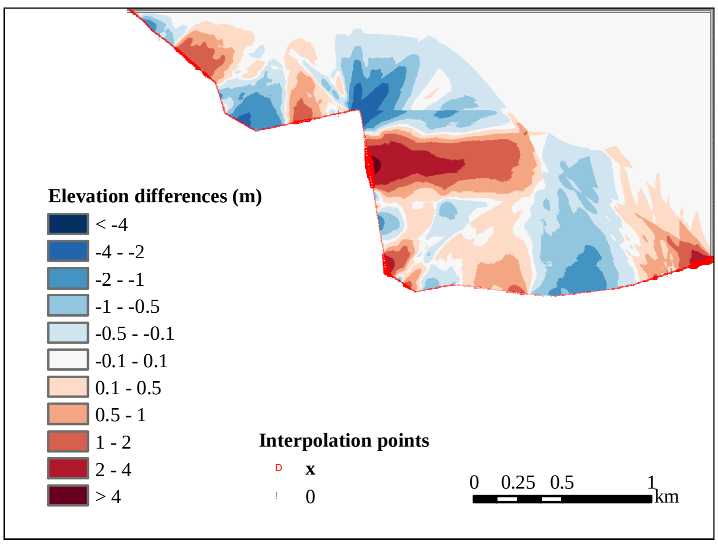


Figure 7. DIF surface obtained from spatial interpolation used with `MBlend` to merge the two DEMs (Study Area 1)

Elevation comparison

A quantitative analysis of the magnitude of the changes performed by each of the methods was conducted in order to compare the results obtained by each of the four tested DEM merging methods. This analysis was conducted in a buffer analysis area, defined as a buffer of 375 m (see Figure 3) around the boundary line between the two original DEMs. In the case of the DEM_{hr} the comparison was only performed in half of the buffer area because it was only available in this area. Using the DEM_{lr} as reference the `Cover` method does not change cell elevation values and the `Average` and `Blend` methods only change cells within the DEMs overlapping area. By contrast, all cells within the buffer analysis area of the merged DEM obtained using `MBlend` had elevation values different from the values of the DEM_{lr} cells. This is explained by the fact that this method changes only cells of the DEM_{lr}, whereas the remaining cells have the original elevation values of the DEM_{hr}.

By comparing the merged DEMs with the DEM_{hr}, it was observed that the application of `MBlend` results in no changes to the DEM_{hr}, which is one of the key objectives of `MBlend`. The same is true for the `Cover` method; however, in this case the DEM showed a terrain discontinuity between the two DEMs (Figure 6a), which may cause problems during DEM-based analysis. Both the `Average` and `Blend` methods change the elevation of the DEM_{hr}.

Slope and aspect comparison

In order to quantify the degree of changes performed by each of the tested methods, the results obtained were also compared against the DEM_{lr} and DEM_{hr} within the buffer analysis area surrounding the boundary between the two original DEMs. The slope was calculated locally using a nine cell window (3x3 cell) sequentially moved over the DEM (Burrough and McDonnell, 1998); a multiple regression was fitted to the nine elevation points in the 3x3 cell window in order to derive the slope from these points.

The slope range, mean and standard deviation values of the original DEMs and merged DEMs can be seen in Table 1. As expected, all values (maximum, minimum and standard deviation slopes) are higher for the DEM_{hr} than for the DEM_{lr}, since low-resolution images are averaged, thereby losing extreme values and consequently terrain details.

Table 1. Summary of slope characteristics of the merged DEMs (Study Area 1)

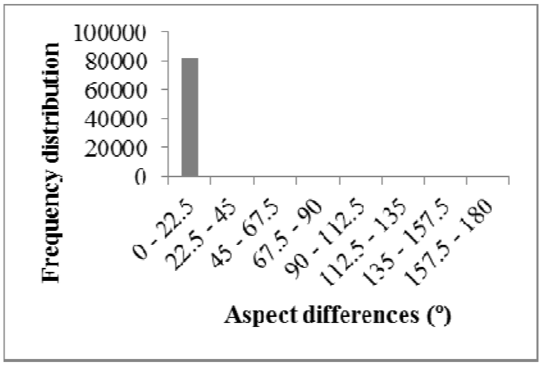
	Minimum	Maximum	Mean	St. Deviation
Slope	**(%)**	**(%)**	**(%)**	**(%)**
DEM_{lr}	0	56.8	4.9	5.6
DEM_{hr}	0	243.4	7.6	8.5
`Cover`	0	**316.8**	6.5	8.4
`Average`	0	158.7	5.4	5.7
`Blend`	0	**56.8**	**4.9**	**5.6**
`MBlend`	0	**243.4**	**6.6**	**7.2**

Taking the DEM_{hr} as reference for the comparison, the resulting merged DEMs should have maximum, mean and standard deviation slope similar to the DEM_{hr}, but no larger. This was the case for the results obtained using `MBlend`; by contrast when the `Cover` method was used, the maximum slope value of the merged DEM showed a significant increase. This high value is caused by the terrain discontinuity along the original DEMs boundary, suggesting that the DEM obtained using this method may create problems when conducting DEM-based analysis.

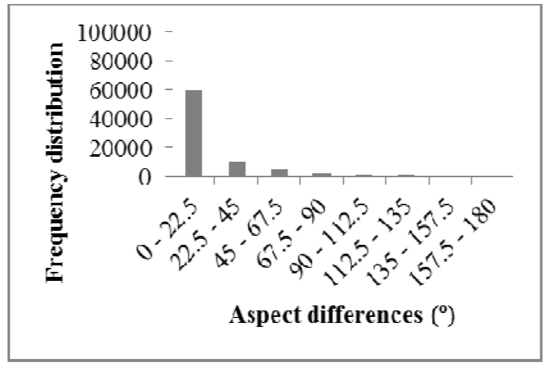
It is also noteworthy that the maximum slope value for the DEM merged using the `Blend` method is very similar to the maximum slope value of the DEM_{lr}; this suggests that the whole observed area becomes over-averaged (or over-smoothed).

As noted before, both the analysis of the aspect values of the merged DEMs and the comparison of these with those of the original DEMs are crucial to assess the quality of the DEMs (for example in overland flow modelling). The aspect values of the merged DEMs are very similar to those of the original DEMs, as can be seen in Figures 8 and 9, which present the aspect differences between the merged DEMs and the DEM_{hr} and the DEM_{lr}, respectively (aspect differences are expressed in bins of 22.5°, differences below this value are considered not significant). It is clear that the aspect values within the buffer analysis area are the same as the DEM_{hr} as when using `MBlend` (Figure 8d). The main aspect difference in terms of aspect values is linked to the number of flat cells of the DEM_{lr} in this specific case (20.9% of the cells of the DEM_{lr} in the buffer analysis area are flat, i.e. aspect equal to -1). The values of these cells are changed when using `MBlend` (Figure 8d) because the elevation of the DEM_{lr}

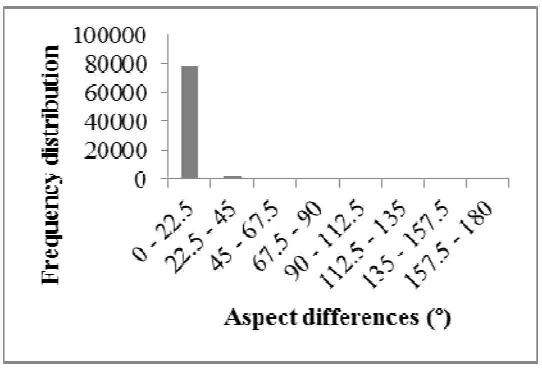
is adjusted according to the values of the DIF surface, which, as a secondary effect, reduces the number of flat cells.



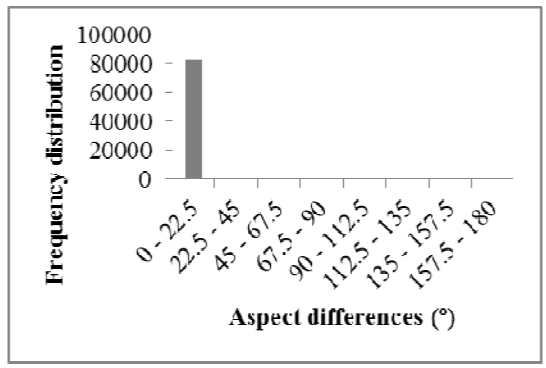
(a) `Cover` method (100% of the cells have similar aspect)



(b) `Average` method (73.1% of the cells have similar aspect)

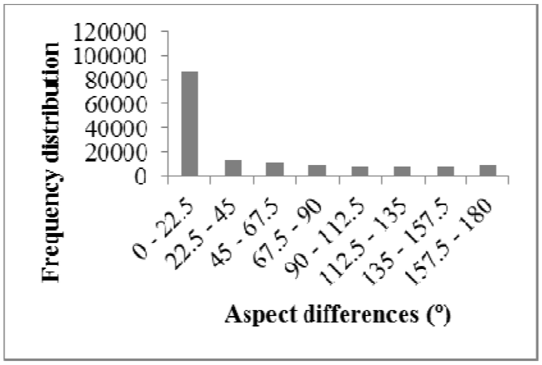


(c) `Blend` method (94.7% of the cells have similar aspect)

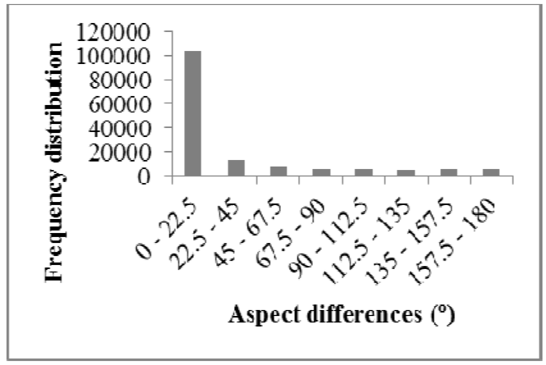


(d) `MBlend` (100% of the cells have similar aspect)

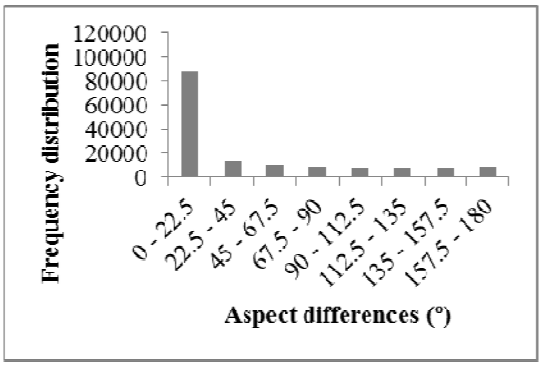
Figure 8. Differences of aspect cell values between the DEM_{hr} and merged DEMs within the 375 m buffer analysis area (Study Area 1)



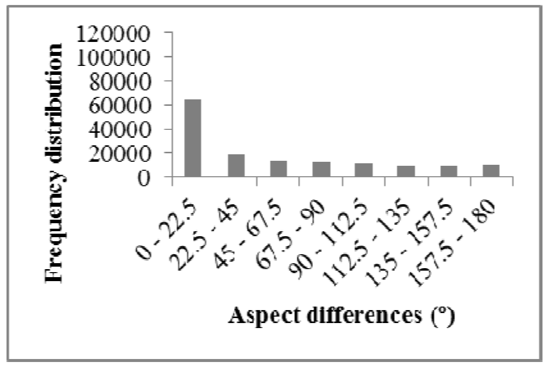
(a) `Cover` method (56.6% of the cells have similar aspect)



(b) `Average` method (67.6% of the cells have similar aspect)



(c) `Blend` method (57.3% of the cells have similar aspect)



(d) `MBlend` (42.6% of the cells have similar aspect)

Figure 9. Differences of aspect cell values between the DEM_{lr} and merged DEMs – 375 m buffer analysis area (Study Area 1)

4.3 Study Area 2 results

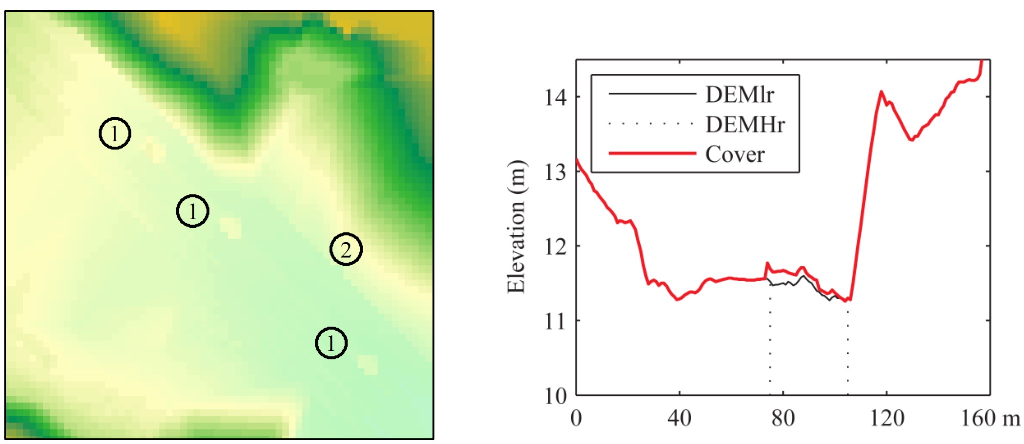
The elevation differences between the two available DEMs considered in this study area vary between -1.25 and 0.6 m. The majority of the elevation differences are small, i.e. between -0.25 and 0.25 m.

Terrain continuity comparison

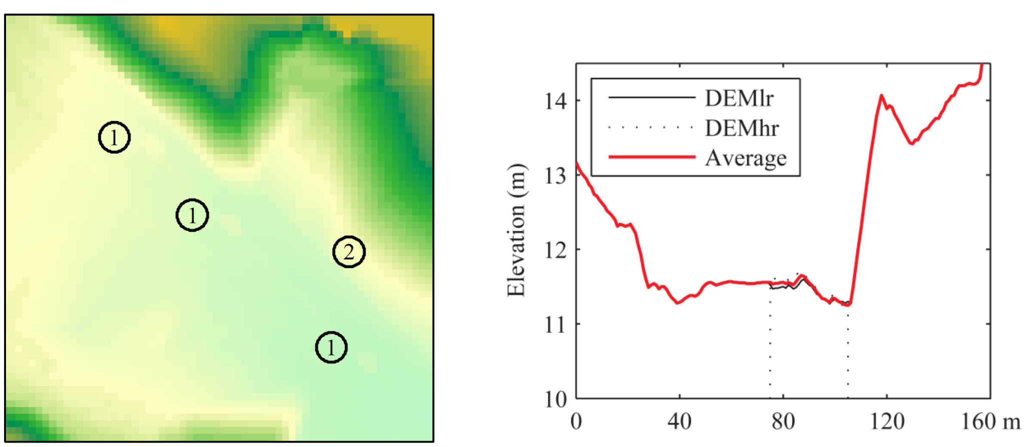
Figure 10 shows the DEMs and elevation profiles obtained using the four DEM merging methods (DEMs boundary occurs at around 80 m on the horizontal axis of the elevation profiles). There are some visible differences when Figures 10a, 10b, 10c and 10d are compared. In Figure 10a (`Cover` method) it is possible to see three urban (man-made) features (locations ①) along the DEM_{hr}, meaning that the details of this DEM are retained; however, across the boundary of the two DEMs and mainly in the right boundary, an abrupt terrain discontinuity, visible as a sharp line between the two green lines is noticeable (location ②).

In Figure 10b (`Average` method) both the urban feature details (locations ①) and the discontinuity along the DEMs boundary (location ②) become slightly blurred. In the case of the DEM merged using the `Blend` method, the urban features are not visible, and the terrain discontinuity is smooth (see Figure 10c). Analysing the elevation profile in Figure 10c, it can be seen that the resulting merged DEM using the `Blend` method (in this particular case of a DEM_{hr} completely overlapping the DEM_{lr}) does not take into account the elevation information of the DEM_{hr}. This is confirmed by analysing the changes in aspect between the merged DEM and the original DEM_{hr} and DEM_{lr} (Figures 12 and 13).

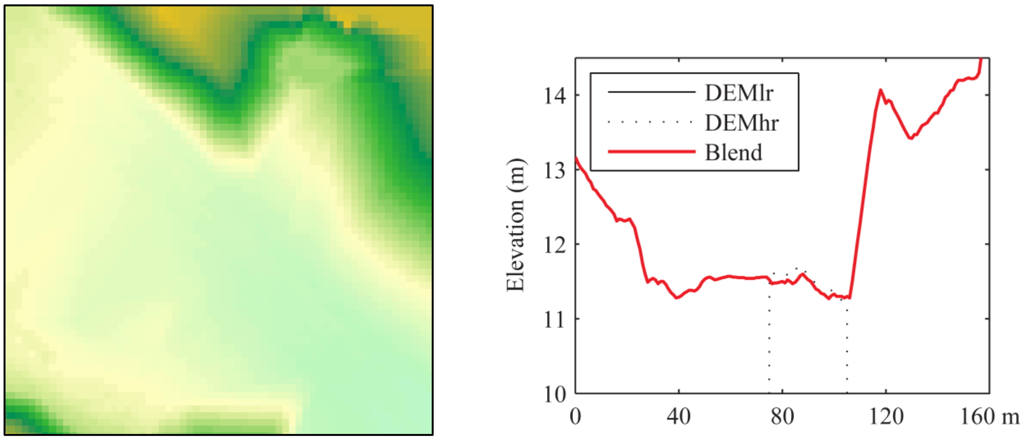
As can be seen in Figure 10d, `MBlend` preserves the detailed information of the DEM_{hr} while retaining the details of urban features (locations ①), and at the same time smooths the elevation transition between the two original DEMs. The DIF surface used with `MBlend` is presented in Figure 11.



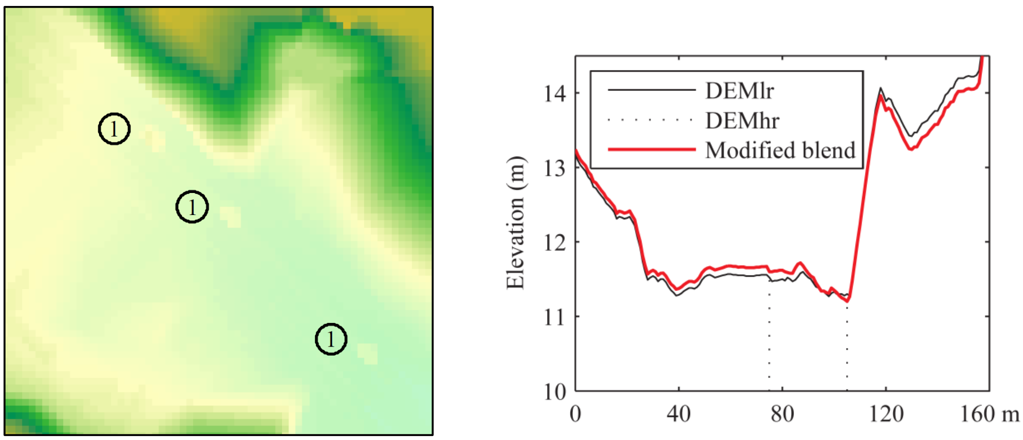
(a) `Cover` method



(b) `Average` method



(c) `Blend` method



(d) `MBlend`

Figure 10. Results of DEM merging – DEMs boundary occurs at around 80 m on the horizontal axis of the elevation profiles (Study Area 2)

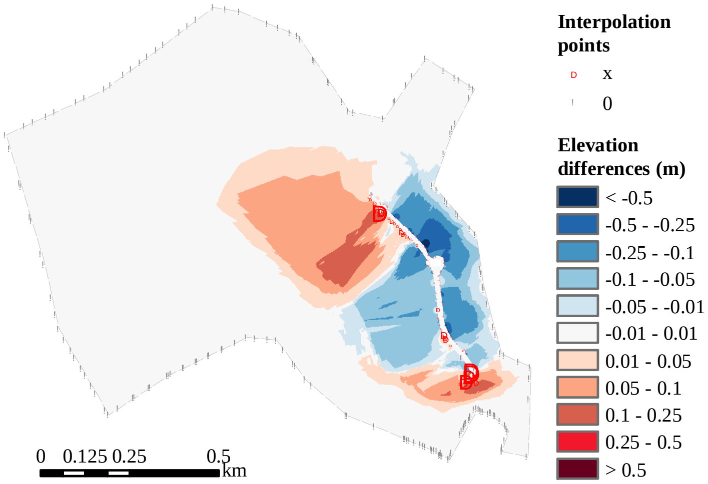


Figure 11. DIF surface obtained from spatial interpolation used with `MBlend` to merge the two DEMs (Study Area 2)

Elevation comparison

The merged DEMs were compared with the original DEMs in terms of number and percentage of cells changed over the area of analysis within a buffer analysis area defined by a 75 m buffer surrounding the boundary of the two original DEMs (Figure 4). `MBlend` operates approximately 10 times more changes than the other three methods when the DEM_{lr} is used as reference. The number of cells changed during the merging process using `MBlend` can be limited by adding a third set of points or moving the points on the boundary of the DEM_{lr} towards the boundary of the two DEMs; the result of these two approaches is especially interesting when the DEM_{hr} represents a linear feature, such as the road in Study Area 2.

When the merged DEMs are compared with the DEM_{hr}, the number of cells changed is different to the number obtained when the merged DEMs are compared with the DEM_{lr}. No cells are changed by `MBlend` or the `Cover` method in DEM_{hr}, whereas the other two methods change more than 90% of the cells within the buffer analysis area. Although this suggests that the DEM merging performance of the `Cover` method is similar to that of `MBlend`, this is not the case. `MBlend` smooths the elevation transition between the two original DEMs, while the DEMs produced by the `Cover` method have an elevation discontinuity along the original DEMs boundary (location ② in Figure 10a).

The results obtained in this study area demonstrate that none of the four DEM merging methods tested cause significant changes in the original DEMs. However, the way each method changes the DEMs is different. Although `MBlend` performs changes in more cells when the DEM_{lr} is used for comparison within the buffer area, it is the only method that creates a smooth transition between the two original DEMs, while retaining the elevation values of the DEM_{hr} during the merging process.

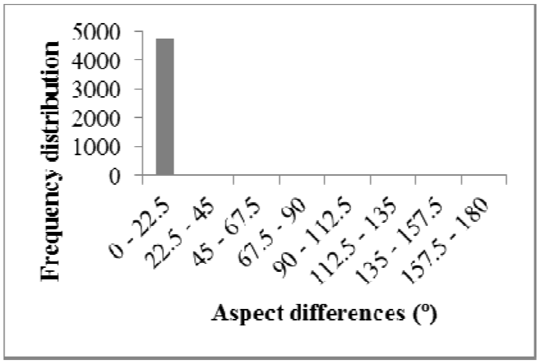
Slope and aspect comparison

Changes in slope and aspect were assessed also within the buffer analysis area (delineated from 75 m from the boundary of the original DEMs). Table 2 presents the results from all four methods and shows that the slope range is not altered and the changes in the mean and standard deviation values are negligible. The slope statistics, specifically the Standard deviation calculated for the merged DEM obtained using the `Blend` method, suggest that the DEM_{hr} might not influence the obtained merged DEM, as this value is the same as for the DEM_{lr}.

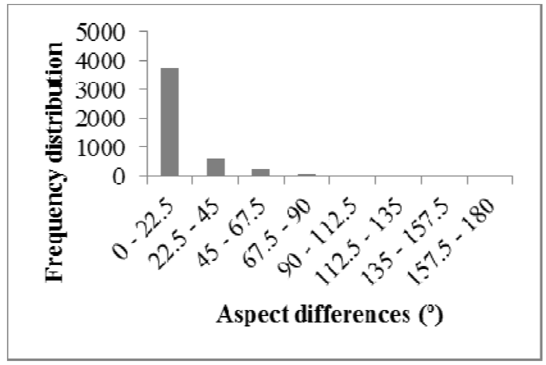
Table 2. Summary of slope characteristics of the merged DEMs (Study Area 2)

	Minimum	**Maximum**	**Mean**	**St. Deviation**
Slope	**(%)**	**(%)**	**(%)**	**(%)**
DEM_{lr}	0	406.8	28.2	44.8
DEM_{hr}	0	54.0	4.4	3.8
`Cover`	0	406.8	28.2	44.9
`Average`	0	406.8	28.2	44.9
`Blend`	0	406.8	28.2	**44.8**
`MBlend`	0	406.8	28.2	44.9

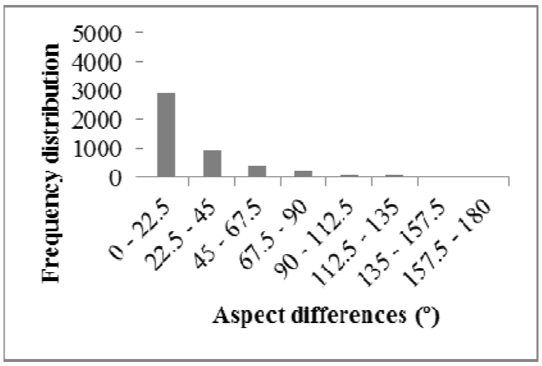
The aspect values of the merged DEMs are not significantly different from the aspect values of the original DEMs (Figures 12 and 13). It is noteworthy that the DEMs produced by the `Cover` method and `MBlend` have similar aspect values to those of DEM_{hr}.



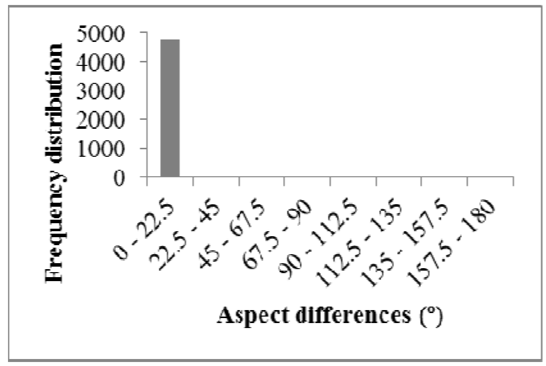
(a) `Cover` method (100% of the cells have similar aspect)



(b) `Average` method (78.3% of the cells have similar aspect)

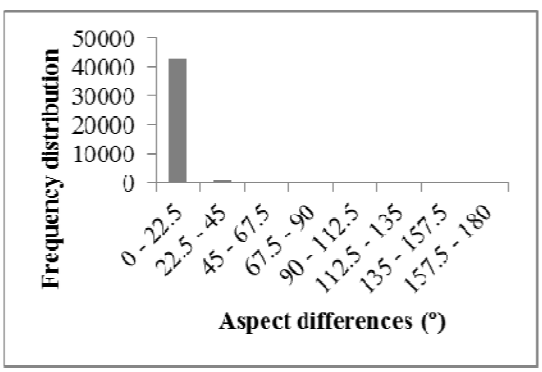


(c) `Blend` method (61.3% of the cells have similar aspect)

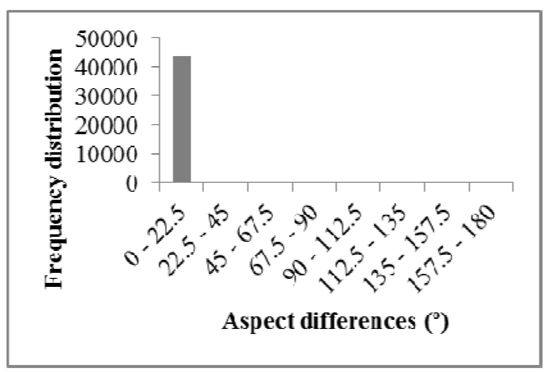


(d) `MBlend` (100% of the cells have similar aspect)

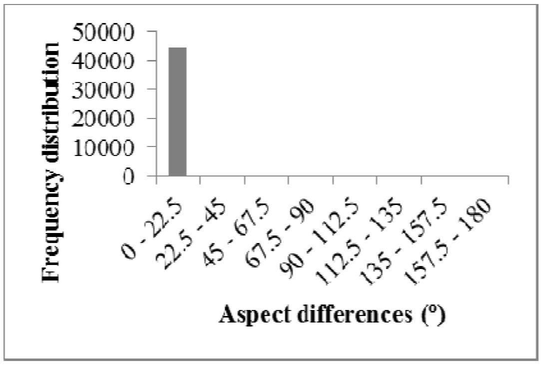
Figure 12. Differences of aspect cell values between the DEM_{hr} and merged DEMs within the 75 m buffer area (Study Area 2)



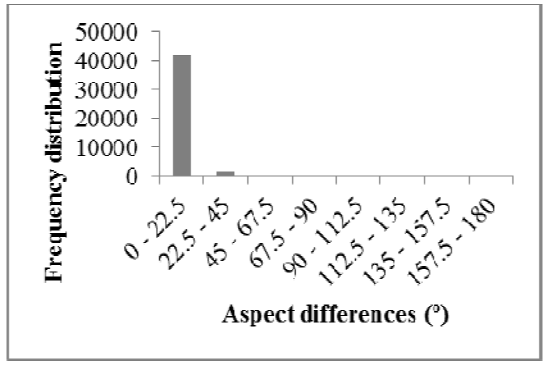
(a) `Cover` method (96.2% of the cells have similar aspect)



(b) `Average` method (98.4% of the cells have similar aspect)



(c) `Blend` method (100% of the cells have similar aspect)



(d) `MBlend` (94.4% of the cells have similar aspect)

Figure 13. Differences of aspect cell values between the DEM_{lr} and merged DEMs – 75 m buffer area (Study Area 1)

One significant difference between the results obtained in Study Area 1 and in Study Area 2 is that in Study Area 2 the number of cells with different aspect (> 22.5º) obtained using `MBlend` is significantly smaller; this difference is due to the smaller number of flat cells of the DEM_{lr} in Study Area 2.

5. Conclusions

When two or more DEMs for the same area are available, those with the highest resolution and best vertical accuracy should be considered as the reference basis for the representation of terrain features. However, if the higher-resolution DEM does not cover the whole area, it should be merged with a larger, lower-resolution DEM in order to accurately represent the full area. During the merging procedure, changes to the higher-resolution DEM should be avoided; elevation adjustments should be performed only on the lower-resolution DEM.

Unlike the conventional DEM merging methods, the new method presented in this paper, called `MBlend`, merges two DEMs by adjusting only the elevation of the low-resolution and less accurate DEM; the level of accuracy of the highest resolution DEMs is thereby retained, ensuring also correct terrain slope and aspect across the two DEMs boundary.

Results obtained from tests carried out using four real DEMs in two different areas and the DEM merging methods considered in this study (`Cover`, `Average`, Blend and MBlend) showed that MBlend consistently produces smooth elevation transitions between the two DEMs; slope and aspect calculated from the merged DEM are also not significantly altered when compared to the original slope values. Unlike other methods (Warriner and Mandlburger, 2005), MBlend does not require *a priori* definition of the area where elevation adjustments occur. The area is automatically defined based on the cell values of the original DEMs' elevation differences (DIF surface); the generation of the DIF surface is a crucial step in the method, and may have a significant effect on the accuracy of the merged DEM.

The spatial interpolation algorithm and the number and distribution of the points used in the interpolation process influences the performance of MBlend. Future work should focus on comparing different interpolation algorithms (e.g., Splines, Multiquadratic or stochastic methods such as Kriging) to generate the elevation differences surface (DIF). Another area of experimentation should be the density and location of the sample points which limit the extent of the area where the elevation adjustments occur. Although the quality of the merged DEM in terms of elevation transition between the two original DEMs and retention of original elevation in the high-resolution DEMs was not affected when different locations and/or number of interpolation points were used, future work should also investigate the effect of the elevation values assigned to the points in the low-resolution boundary. In this study, an elevation value of 0 m was assigned to these points; however, other values, such as the average of the elevation differences between the two DEMs within the overlapping area, or the elevation differences average calculated along the DEMs common boundary can be assigned to these points. The impact of these various MBlend options (e.g., different interpolation algorithms, different sets of points used for generating the DIF surface) needs to be assessed based on quantitative indicators; this should certainly include the possibility to quantify the quality and continuity of resulting overland flow paths. With adequate quantification, it would be even possible to formulate a criterion function and use optimization techniques to search for the best possible merged DEM.

In this paper we have presented a new method, MBlend, for merging DEMs with different characteristics, e.g., resolution and levels of terrain detail. The results obtained using MBlend were compared with those obtained using three merging methods available in most GIS software. The comparison showed that DEMs merged using MBlend retain the elevation details of the most accurate DEM (called DEM_{hr} in this study), and that terrain discontinuity issues that may exist along the original DEMs boundary are also resolved. The DEMs merged using `MBlend` allow for the integration of newly available DEMs with very high resolution and associated terrain detail (e.g., DEMs generated based on UAVs), contributing to more accurate terrain analysis and, specifically, more accurate one-and two-dimensional overland flow modelling studies in urban areas. We also expect `MBlend` to be applicable to other raster images, such as rainfall images.

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