Computers & Geosciences 88 (2016) 115–131

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Case study

Improving merge methods for grid-based digital elevation models

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ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form
24 October 2015
Accepted 5 January 2016
Available online 6 January 2016

Keywords:
Data merging
Digital elevation models
Grid-based rasters
Terrain analysis

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.

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 most of the terrain analysis applications, such as overland flow modelling and 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 overland flow 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 DEM 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) (Küng 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.

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 overland flow patterns resulting in unrealistic overland flow 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

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http://dx.doi.org/10.1016/j.cageo.2016.01.001
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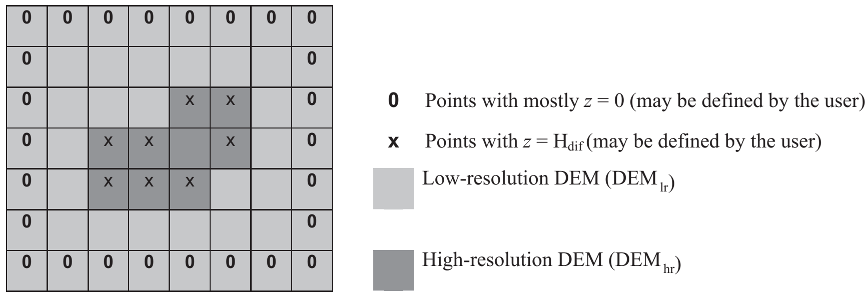


Fig. 1. Possible location of points used to generate the DIF surface (interpolation points).

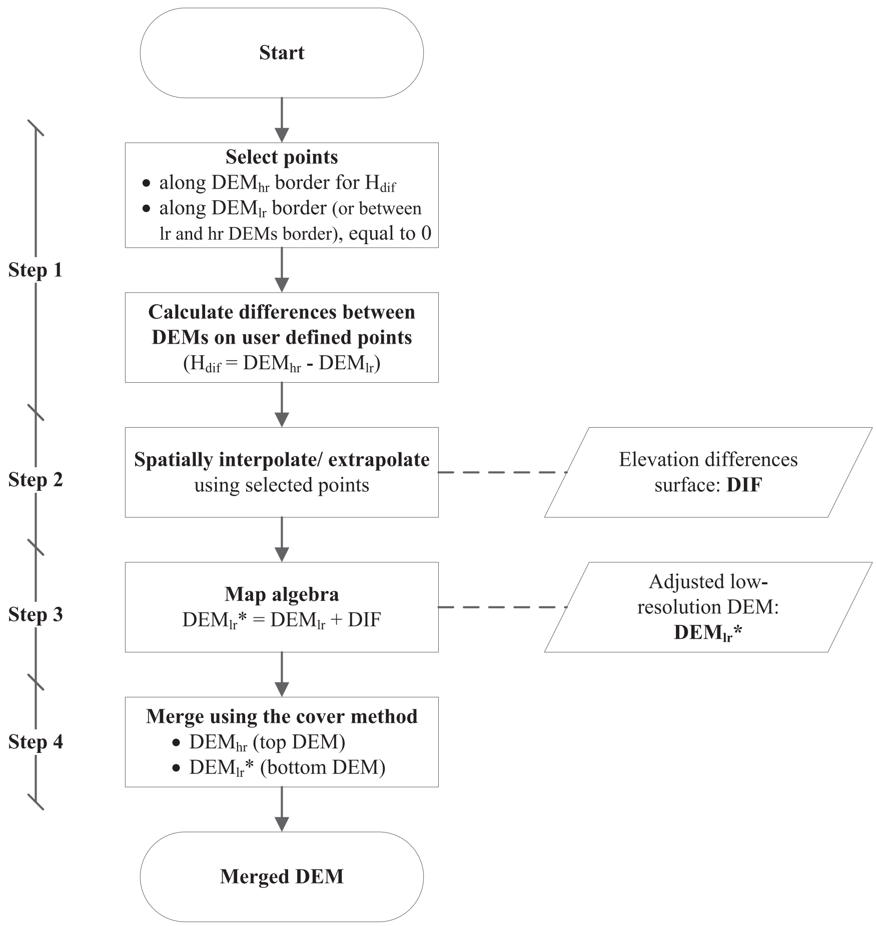


Fig. 2. Flowchart of `MBlend`.

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 et al., 2004).

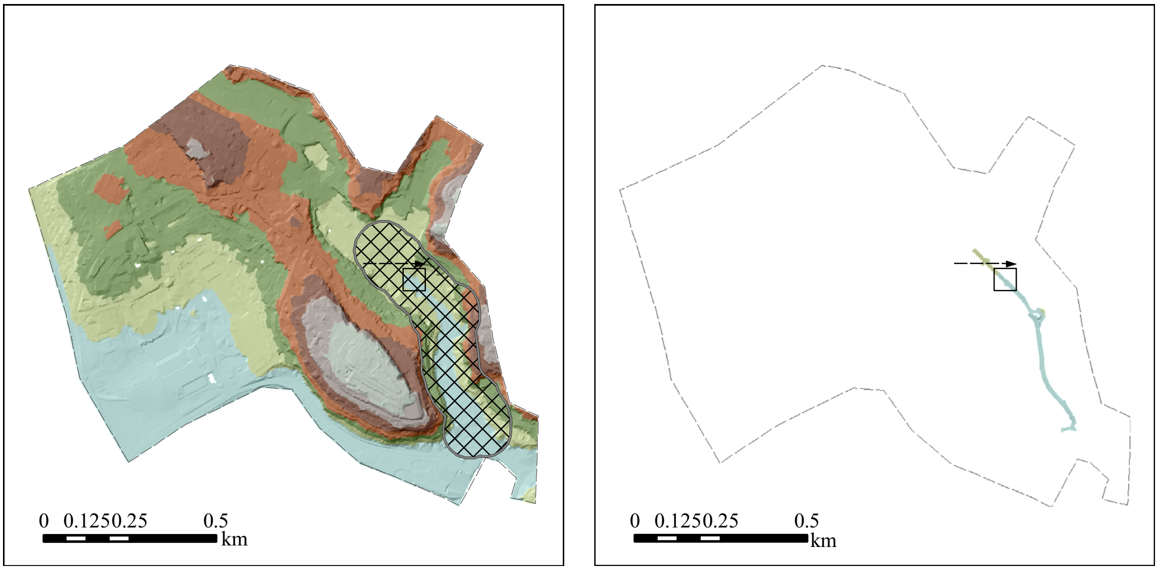
1.2. Conventional DEM merging methods

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 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).

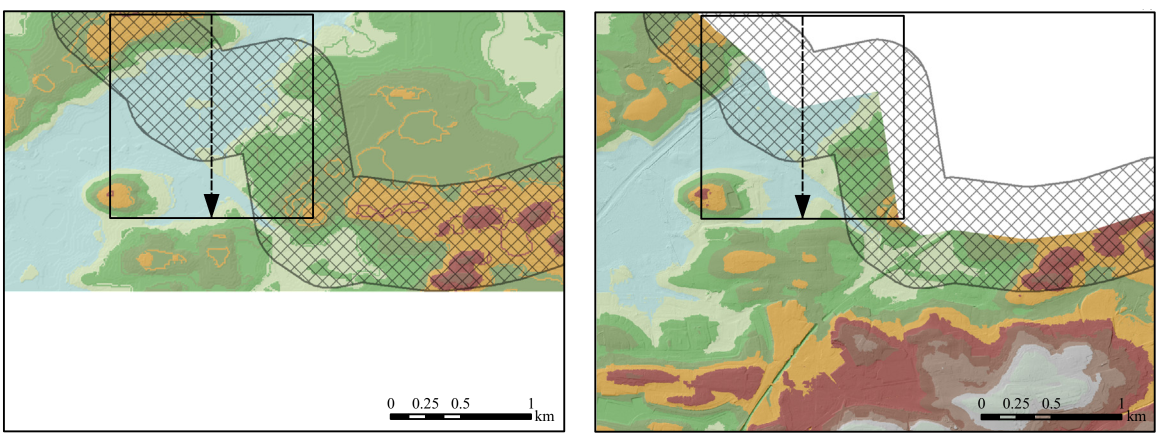
In the `Average` and `Blend` methods, elevation adjustments are performed within the overlapping area of the DEMs being merged. `Average` methods assign the average value of the elevation within the overlapping area of the two DEMs. Hence, only the elevation values within the overlapping area are changed.

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



(a) low-resolution DEM (airborneLiDAR) (b) high-resolution DEM (ground-basedLiDAR)

Fig. 3. Study Area 1 DEMs. The solid line bounded square and the dashed line will be used in Fig. 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. (a) low-resolution DEM (airborne LiDAR), (b) high-resolution DEM (ground-based LiDAR).



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

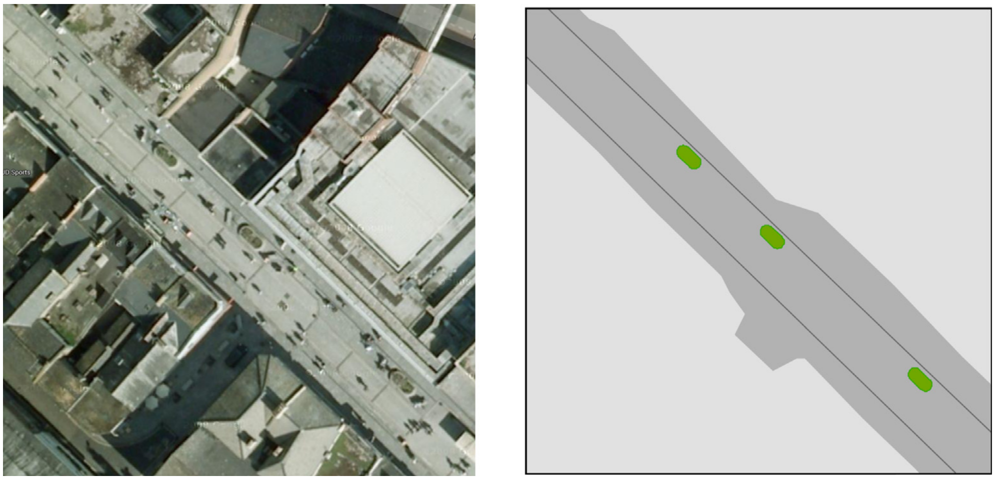
Fig. 4. Study Area 2 DEMs. The solid line bounded square, 1450 × 1450 pixel, and the dashed line will be used in Fig. B.2, which presents the results of the merging methods and the elevation profiles; the meshed area will be used in the evaluation of the slope and aspect differences between the original and merged DEMs. (a) low-resolution DEM (cartographic), (b) high-resolution DEM (airborne LiDAR).

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. 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 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.



(a) aerial photograph (Google, 2015) (b) Street elements (green - planters; grey lines are street curbs; dark and light grey areas represent the high- and low-resolution DEMs, respectively)

Fig. 5. Detailed area of analysis. (a) aerial photograph (Google, 2015), (b) Street elements (green - planters; grey lines are street curbs; dark and light grey areas represent the high- and low-resolution DEMs, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 DEM merging methods available in the commercial GIS software 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

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` 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.

In the second step, selected points along the common boundary of the two DEMs (marked with **X** on Fig. 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 **0** on Fig. 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.

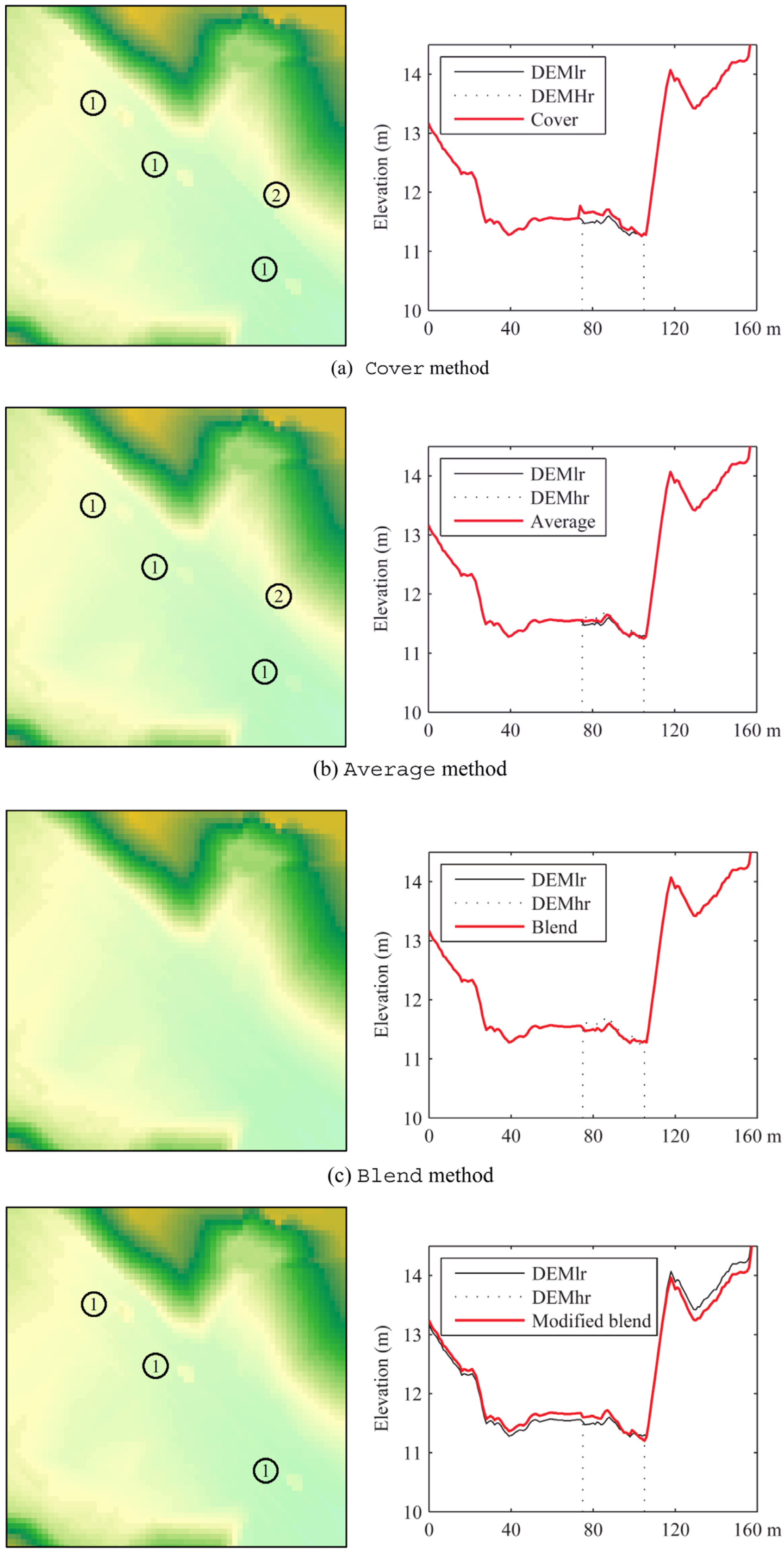
The third step consists of adding the DIF surface representing the elevation differences to the low-resolution DEM in order to create an updated low-resolution, DEM (Eq. (1)).

$$z_{lr^*(i,j)} = z_{lr(i,j)} + z_{DIF(i,j)}, \quad (1)$$

where $z_{lr^*(i,j)}$ is the elevation value of the updated low-resolution DEM in the cell *i*,*j*, $z_{lr(i,j)}$ is the elevation value of the low-resolution DEM in the cell *i*,*j*, $z_{DIF(i,j)}$ is the elevation difference calculated between the high- and the low resolution DEM in the cell *i*,*j*.

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. Fig. 2 presents a flowchart describing the steps of `MBlend`.

`MBlend` has significant advantages when compared to the conventional DEM merging methods. With `MBlend` the band width



(a) Cover method

(b) Average method

(c) Blend method

(d) MBlend

Fig. 6. Results of DEM merging. The left-hand side images correspond to the Digital Elevation Model of the detailed analysis area (solid bounded square in Fig. 3; Locations ① represent planters and Location ② represents the boundary between the two DEMs original DEMs); the right-hand side images correspond to the elevation profile along the line presented in Fig. 3). DEMs boundary occurs at around 80 m on the horizontal axis of the elevation profiles (Study Area 1). (a) Cover method, (b) Average method, (c) Blend method, (d) MBlend.

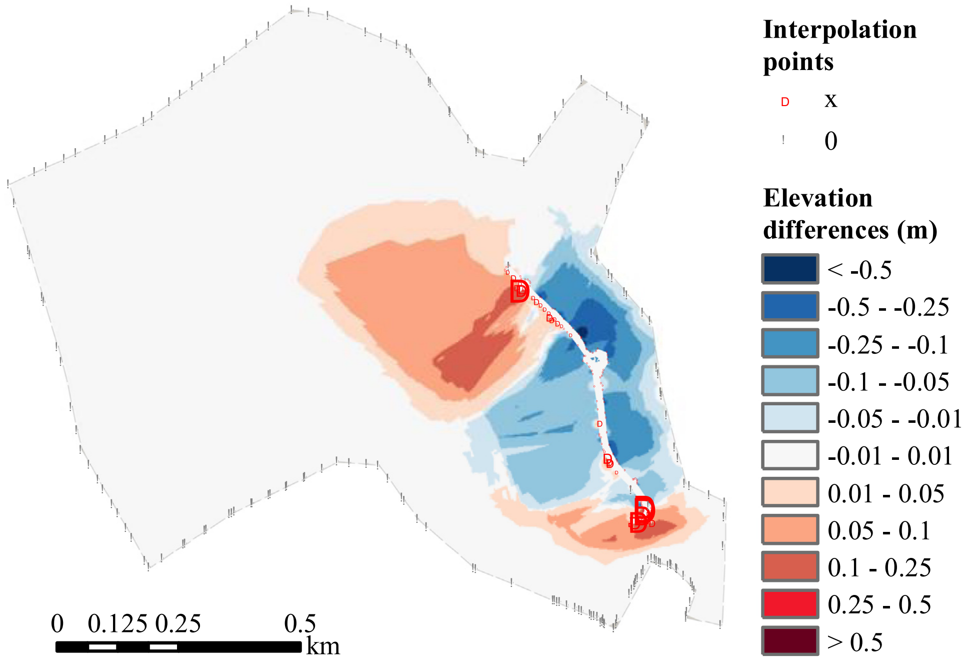


Fig. 7. DIF surface obtained from spatial interpolation used with `MBlend` to merge the two DEMs (Study Area 1).

Table 1
Goodness-of-fit measures to quantify elevation differences between original and merged DEMs.

DEM merging method	Cells changed		MAE*	d_1**
	(number)	(%)	(m)	(-)
DEM_{lr} (total number of cells: 130,860)				
Cover	10,024	7.7	0.005	1.000
Average	10.058	7.7	0.002	1.000
Blend	8884	6.8	0.000	1.000
MBlend	129,515	99.0	0.093	0.994
DEM_{hr} (total number of cells: 10,644)				
Cover	0	0	0.000	1.000
Average	10,058	94.5	0.030	0.990
Blend	10,058	94.5	0.054	0.982
MBlend	0	0.0	0.000	1.000

* Mean Absolute Error is defined as $MAE = \frac{\sum_{i=1}^{n}|o_i - p_i|}{n}$.

** Modified Index of Agreement is defined as $d_1 = 1 - \frac{\sum_{i=1}^{n}(o_i - p_i)}{\sum_{i=1}^{n}(|p_i - \bar{o}| + |o_i - \bar{o}|)}$.

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

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 Torquay (south west of England); this area covers approximately 1.1 km^2 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 (Fig. 3).

The second area, Study Area 2, 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, Fig. 4a) and the second generated using airborne LiDAR technology (LiDAR DEM, Fig. 4b). The characteristics of the DEMs used in this study are presented in Appendix A.

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.

The results obtained in the two study areas are analogous. The results obtained for the Study Area 1 are presented in the following sub-sections; the results of Study Area 2 are presented in Appendix B.

The IDW spatial interpolation method (Eq. (2)) was applied to generate the DIF surface (see Fig. 2) that is then used to generate the `MBlend` DEM from the two original DEMs (DEM_{lr} and DEM_{hr}).

$$z_i = \frac{\sum_j \frac{z_j}{d_{ij}^n}}{\sum_j \frac{1}{d_{ij}^n}} \quad (2)$$

Where z_i is the interpolated value at point i (x_i, y_i) in the DIF surface, z_j is the value of the j points used for interpolation (x and 0 points, as presented in Fig. 1), d_{ij} is the distance (Euclidian distance, for example) between points i and j, and n is a factor that works as a weight of the distance (usually $n=2$).

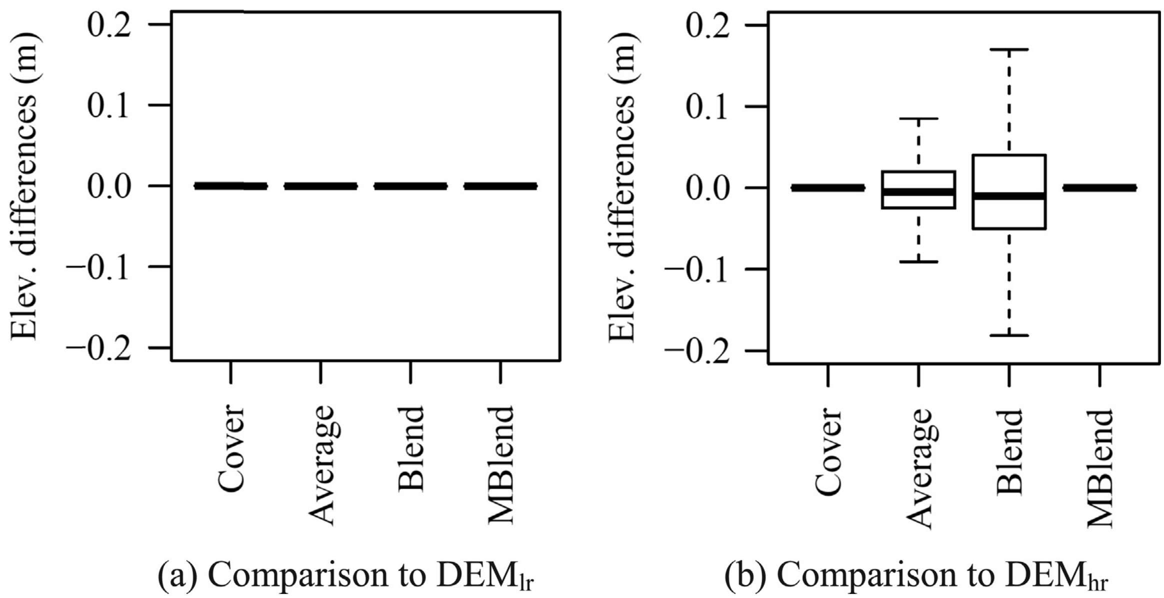


Fig. 8. Residuals of elevation differences between the original and merged DEMs. (a) Comparison to DEM_{lr}, (b) Comparison to DEM_{hr}.

Table 2
Summary of slope characteristics of the merged DEMs (Study Area 1).

Slope	Minimum (%)	Maximum (%)	Mean (%)	St. deviation (%)
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

4.2. Study Area 1

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.

4.2.1. Terrain continuity comparison

To compare the results obtained using the `MBlend` method and the conventional raster merging methods, a detailed area was selected from the overlapping area of the two DEMs – it is presented as the solid line square in Fig. 3. This area was selected because of the existing urban features in this location, such as the planters visible in the aerial photograph (Fig. 5a) and schematically represented in Fig. 5b.

Fig. 6 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 Fig. 6a–d are compared. In Fig. 6a (`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

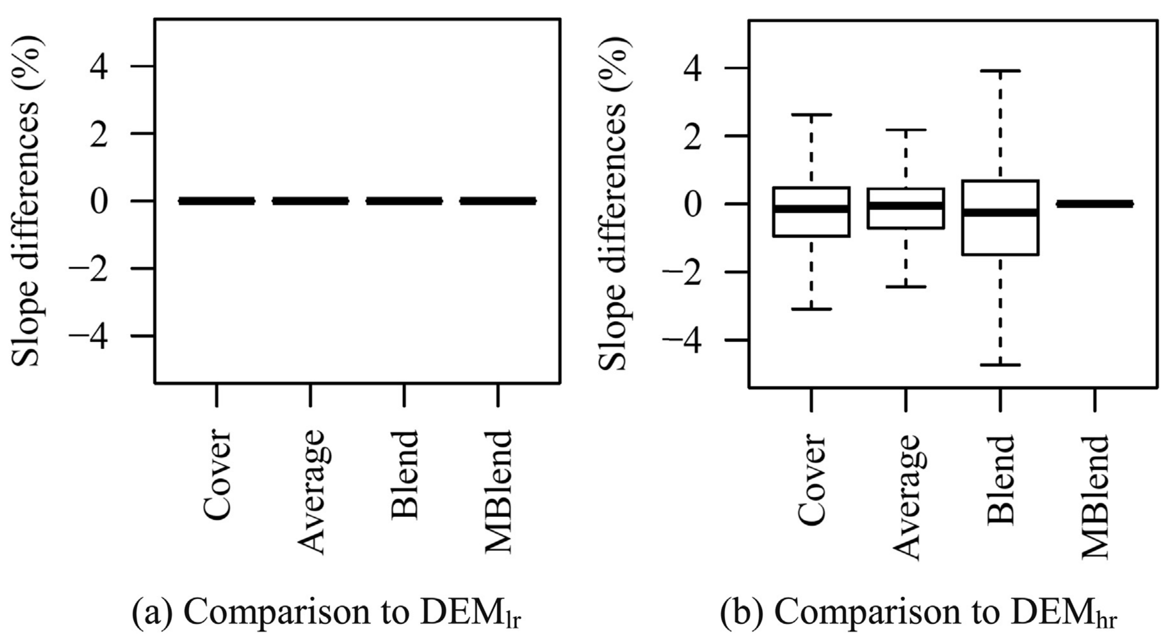


Fig. 9. Residuals of slope differences between the original and merged DEMs. (a) Comparison to DEM_{lr}, (b) Comparison to DEM_{hr}.

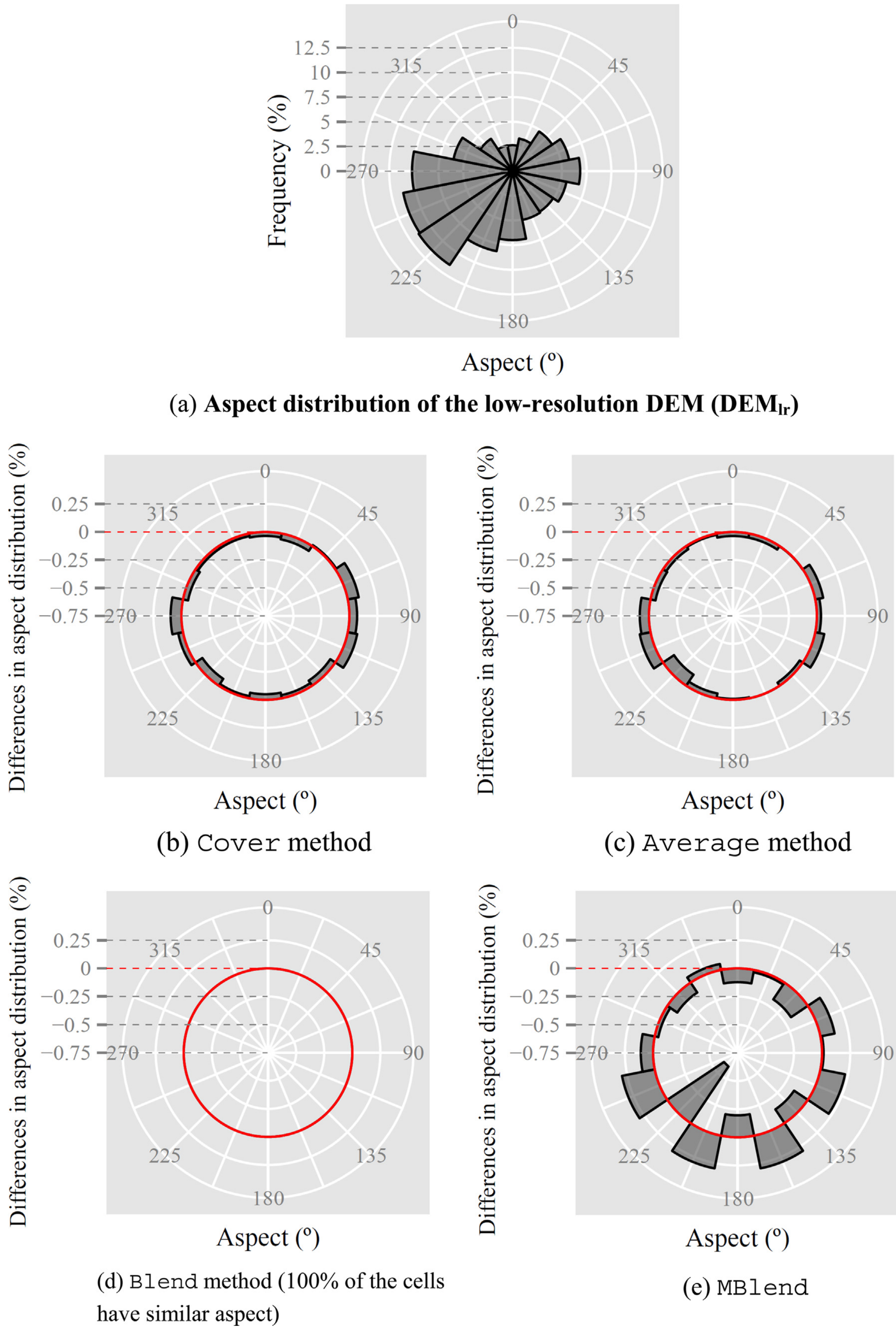


Fig. 10. Differences of aspect distribution between the low-resolution DEM (DEM_{lr}) and merged DEMs – 75 m buffer area (Study Area 1). (a) Aspect distribution of the low-resolution DEM (DEM_{lr}), (b) `Cover` method, (c) `Average` method, (d) `Blend` method (100% of the cells have similar aspect), (e) `MBlend`.

Table 3
Comparison of aspect values between between original and merged DEMs.

Merging method	Coefficient of determination (R^2)	
	DEM_{lr}	DEM_{hr}
`Cover`	0.962	1
`Average`	0.980	0.696
`Blend`	1.000	0.515
`MBlend`	0.923	1

noticeable (location ②).

In Fig. 6b (`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 Fig. 6c). Analysing the elevation profile in Fig. 6c, 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 elevation, slope and aspect between the merged DEM and the original DEM_{hr} and DEM_{lr} (Figs. 8–11).

As can be seen in Fig. 6d, `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. These two characteristics could not be achieved by using conventional DEM merging methods.

The DIF surface used with `MBlend` is presented in Fig. 7. The DIF surface used with `MBlend` and the points used to generate the DIF surface are presented in Fig. 7.

4.2.2. Elevation comparison

To assess the differences of elevation between the original DEMs and merged DEMs, The merged DEMs were compared with the original DEMs in terms of the number and percentage of cells changed, Mean absolute Error (MAE) and Modified Index of Agreement (d_1) within a buffer analysis area defined by a 75 m buffer surrounding the boundary of the two original DEMs (Fig. 3) were calculated; the results are presented in Table 1.

`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 1.

When the merged DEMs are compared with the DEM_{hr}, (130,860 cells) the number of cells changed is different to the number obtained when the merged DEMs are compared with the DEM_{lr} (10,644 cells). 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 Fig. 5a).

The results obtained in this study area demonstrate that none of the four DEM merging methods tested cause significant changes in the original DEMs (Fig. 8). 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.

4.2.3. 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). The slope was calculated locally using a nine cell window (3×3 cell) sequentially moved over the DEM (Burrough and McDonnell, 1998); a multiple regression was fitted to the nine elevation points in the 3×3 cell window in order to derive the slope from these points.

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}.

As can be seen in Fig. 9, the calculated slope differences between the original DEMs and merged DEMs are, in general, small. One feature that is important to highlight is the result of the comparison of the DEM obtained using the `MBlend` method with the DEM_{hr}; in this particular case, the differences are inexistent (Fig. 9(b)).

The aspect values of the merged DEMs are not significantly different from the aspect values of the original DEMs. Fig. 10 (comparison with low-resolution DEM) and 11 (comparison with high-resolution DEM) present the differences in the distribution of aspect between the original and merged DEMs. It is noteworthy that the DEMs produced by the `Cover` method and `MBlend` have similar aspect values to those of DEM_{hr}.

In addition to the plots, Table 3 presents the coefficient of determination (R^2) between the aspect values of the original and merged DEMs. The related QQ plots are not included in the manuscript as no differences can be depicted in the plots – the values of R^2 for all the four methods are higher than 0.92 when the comparison is with the DEM_{lr}. When the merged DEMs are compared with the DEM_{hr}, it is noteworthy that the `Cover` and `MBlend` methods have the same aspect values of the original DEM_{hr} ($R^2 = 1$), whereas the other two methods show a relatively small R^2 (0.696 and 0.515 for the `Average` and `Blend` methods, respectively), meaning that they do not retain the more accurate information of the DEM_{hr} (Fig. 11).

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 and aspect values of DEM_{hr}. Unlike other methods (Warriner and Mandlburger, 2005), `MBlend` does not require *a priori* definition of the area where

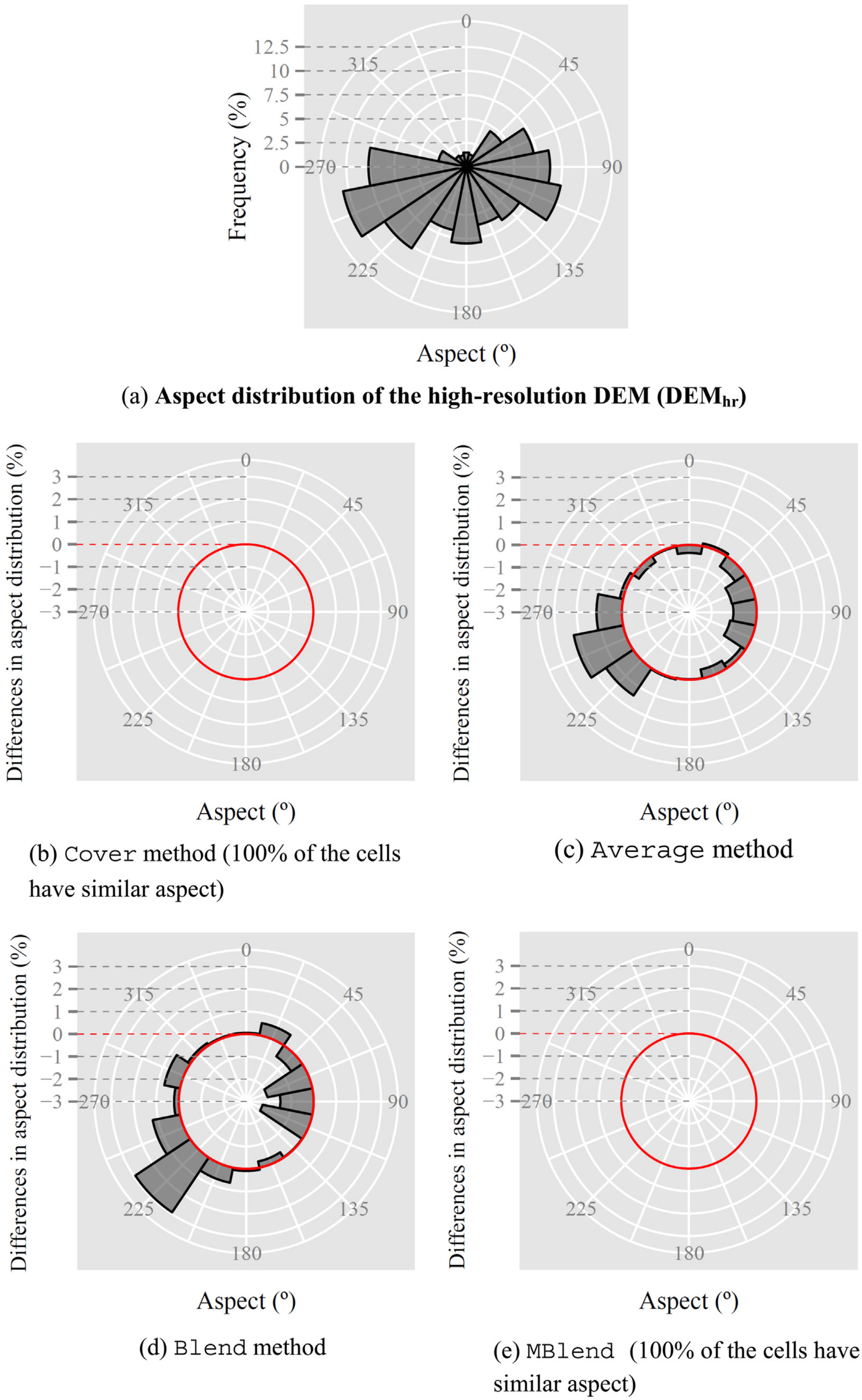


Fig. 11. Differences of aspect distribution between the high-resolution DEM (DEM_{hr}) and merged DEMs – 75 m buffer area (Study Area 1). (a) Aspect distribution of the high-resolution DEM (DEM_{hr}), (b) `Cover` method (100% of the cells have similar aspect), (c) `Average` method, (d) `Blend` method, (e) `MBlend` (100% of the cells have similar aspect).

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). 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 optimisation techniques to search for the best possible merged DEM.

In this paper we have presented a new method, `MBlend`; 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, 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, contributing to more accurate terrain analysis. We also expect `MBlend` to be applicable to other raster images, such as rainfall images.

Acknowledgements

The authors would like to thank David Stewart and Mike Wood from Torbay Council and FRMRC project (http://www.floodrisk.org.uk/) partners by providing the DEMs used in this study.

Appendix A. DEM data sets used in the study presented in this paper

A1 Airborne LiDAR DEMs

Both LiDAR data sets (Study Area 1 and Study Area 2) 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 1 × 1 m) with vertical accuracy of ±0.15 m (Petr et al., 2008). The DEM of Study Area 1 (1477 rows × 1274 columns) covers 100% of the study area (approximately 1.1 km^2) whereas the DEM of Study Area 21 (4000 rows × 3000 columns) covers only 70% (approximately 8.4 km^2).

A2 Ground-based LiDAR DEM

The elevation data used to generate the ground-based LiDAR DEM (300 rows × 535 columns), used in Study Area 1,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 (Fig. 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.

A3 Cartographic (contour) DEM

Ordnance Survey (OS) cartographic elevation data for Study Area 2 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 5000 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 2 catchment; they cover areas outside the catchment boundary, and thus were cropped to the Study Area 2 catchment parts only. To generate the DEM (4000 rows × 2000 columns), the data were first converted to the ESRI point shapefile format, and then interpolated. Although the cell size of the cartographic DEM is 1 × 1 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.

Appendix B. Study Area 2 results

B Study Area 2 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 (Fig. B.1).

From Fig. B.1 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 (approximately 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,

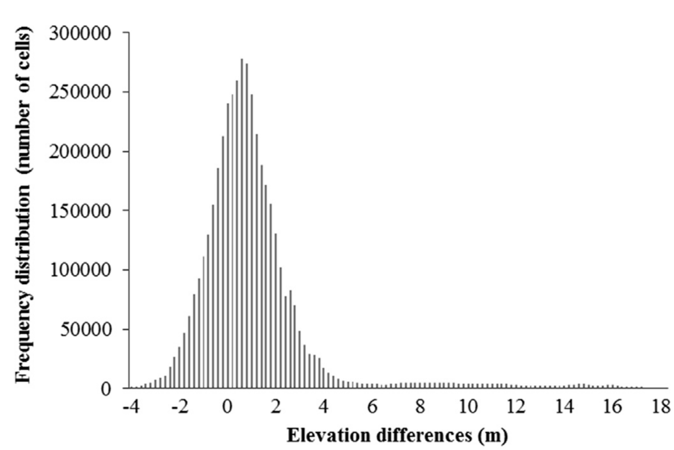
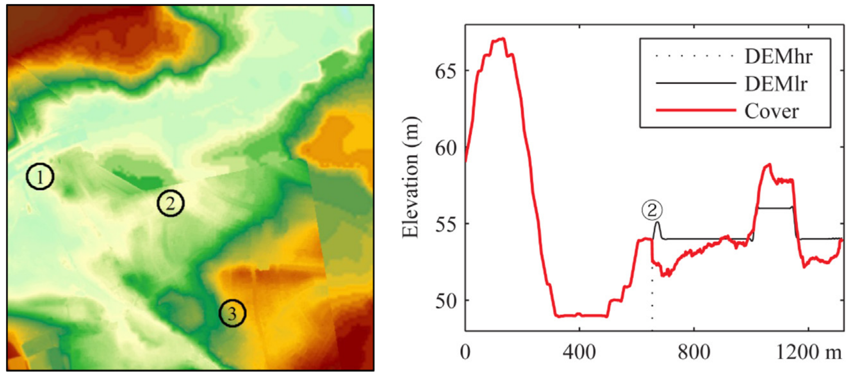
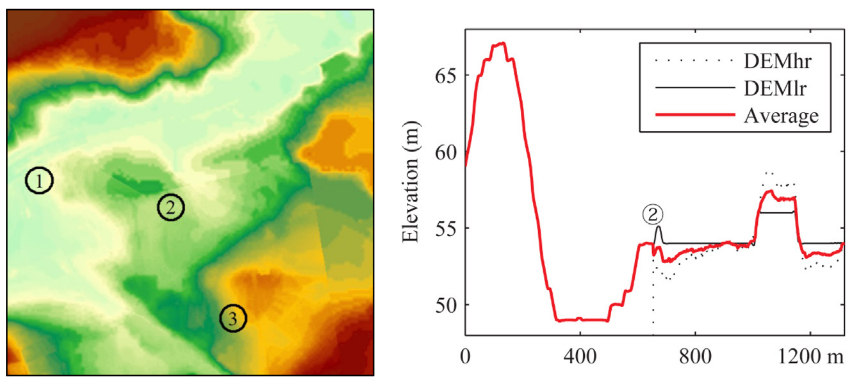


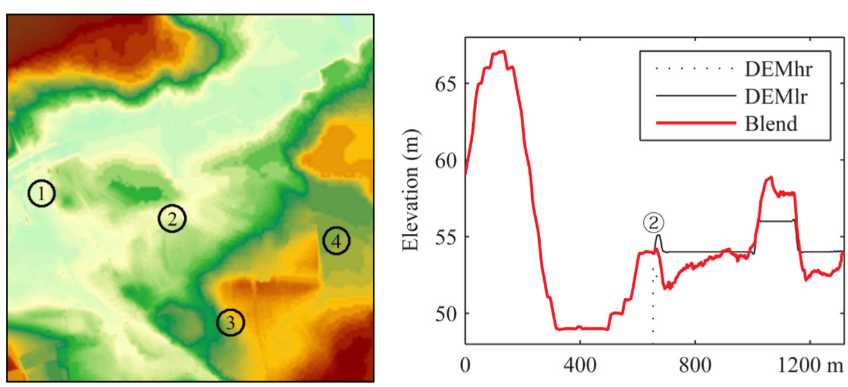
Fig. B.1. Elevation differences between DEM_{hr} and DEM_{lr} (Study Area 2).



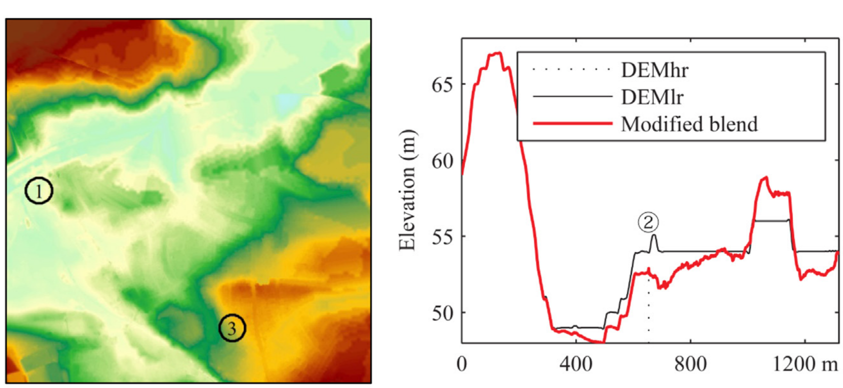
(a) `Cover` method



(b) `Average` method



(c) `Blend` method



(d) `MBlend`

Fig. B.2. Results of DEM merging – DEMs boundary occurs at around 650 m on the horizontal axis of the elevation profiles (Study Area 2). (a) `Cover` method, (b) `Average` method, (c) `Blend` method, (d) `MBlend`.

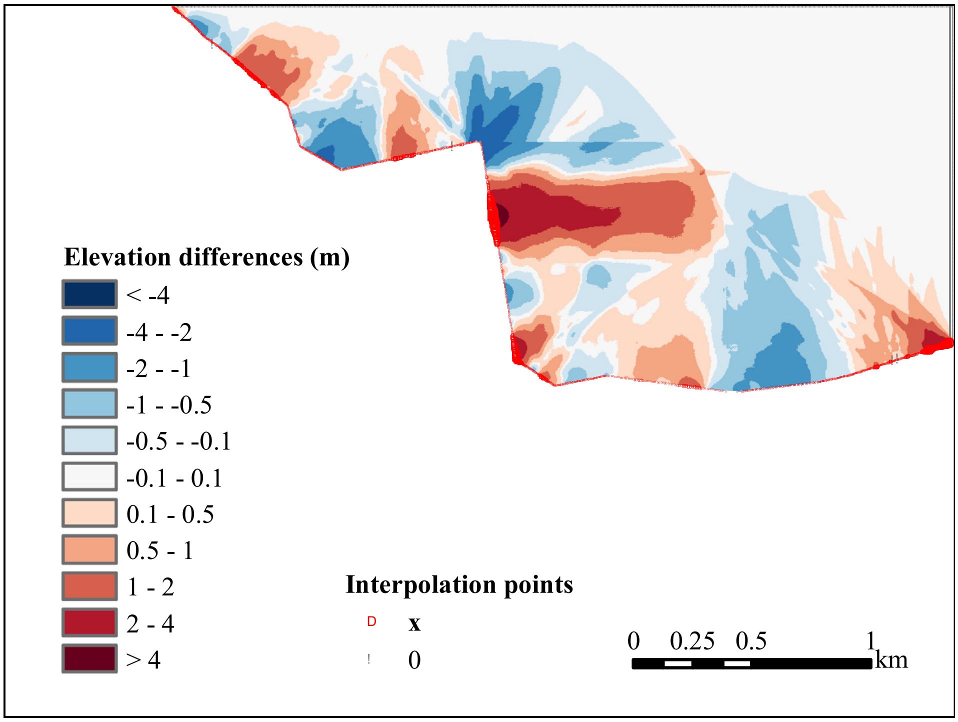


Fig. B.3. DIF surface obtained from spatial interpolation used with `MBlend` to merge the two DEMs (Study Area 2).

Table B.1
Goodness-of-fit measures to quantify elevation differences between original and merged DEMs.

DEM merging method	Cells changed		MAE*	d_1**
	(number)	(%)	(m)	(-)
DEM_{lr} (total number of cells: 2,582,414)				
Cover	1,626,385	53.2	0.702	0.952
Average	1,626,381	53.2	0.351	0.976
Blend	1,622,316	53.1	0.671	0.954
MBlend	3,054,818	100	1.035	0.930
DEM_{hr} (total number of cells: 1,756,929)				
Cover	0	0	0	1
Average	1,626,383	99.9	0.659	0.953
Blend	153,001	9.4	0.058	0.996
MBlend	0	0	0	1

* Mean Absolute Error is defined as $MAE=\frac{\sum_{i=1}^{n}|o_i-p_i|}{n}$.

** Modified Index of Agreement is defined as $d_1=1-\frac{\sum_{i=1}^{n}(o_i-p_i)}{\sum_{i=1}^{n}(|p_i-\bar{o}|+|o_i-\bar{o}|)}$.

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 Fig. B.2. 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 Fig. B.2).

The `Cover` method (Fig. B.2a) 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 Fig. B.2a). 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 Fig. B.2b) as the high accuracy elevation of DEM_{hr} (see ③ in Fig. B.2b). 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 Fig. B.2b). Fig. B.2c 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 Fig. B.2c). The transition achieved between the two DEMs is generally smooth; however, at location ④ of Fig. B.2c, 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 Fig. B.2d). The area where the changes occur is determined by the DIF interpolated surface (see Fig. B.3) created during the methodology process, which in turn is influenced by the elevation differences between the two DEMs, and by the interpolation method used.

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 Fig. 4) 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; this area is represented by 2,582,414 cells and 1,756,929 cells for the DEM_{lr} and DEM_{hr} cases, respectively. The results are presented in Table B.1.

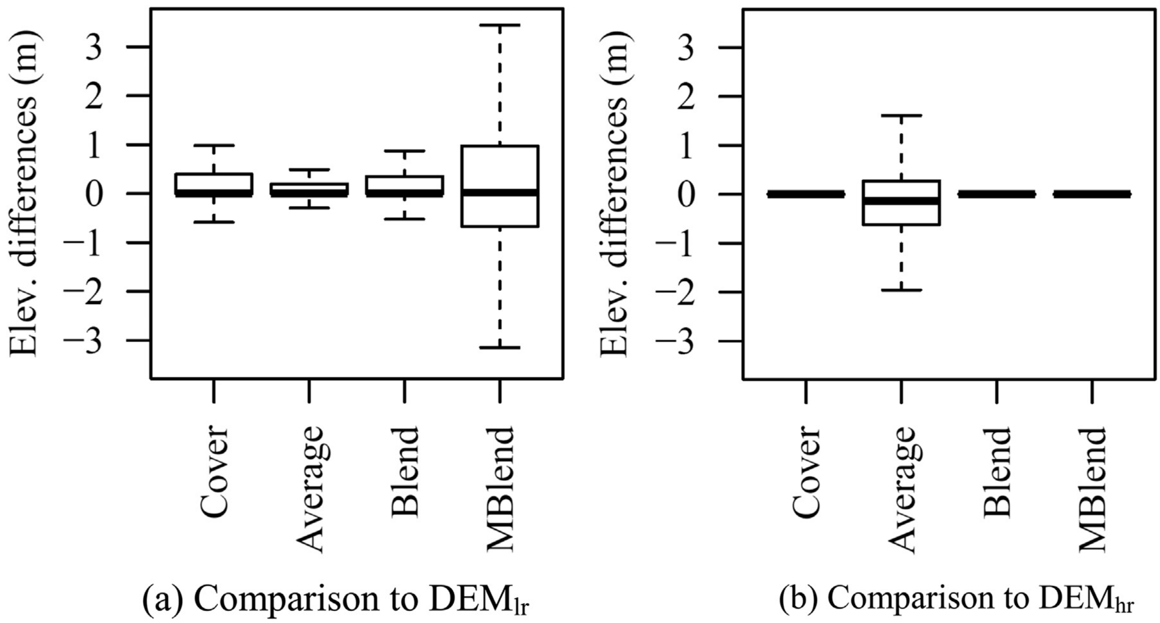


Fig. B.4. Residuals of elevation differences between original and merged DEMs. (a) Comparison to DEM_{lr}, (b) Comparison to DEM_{hr}.

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

Slope	Minimum (%)	Maximum (%)	Mean (%)	St. deviation (%)
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**

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 (Fig. B.2a), which may cause problems during DEM-based analysis. Both the `Average` and `Blend` methods change the elevation of the DEM_{hr}. Fig. B.4 illustrates these results.

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.

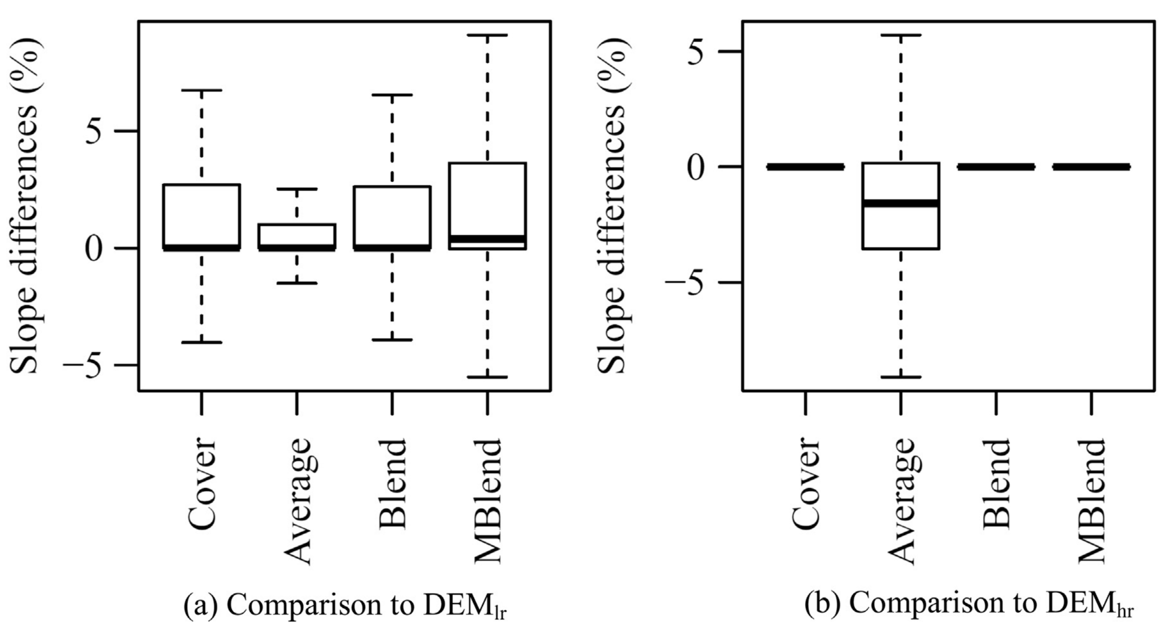
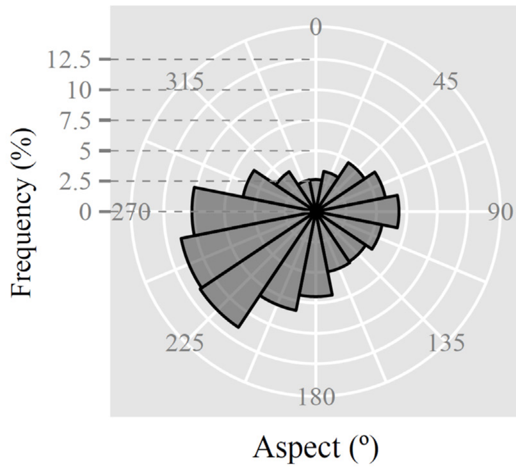
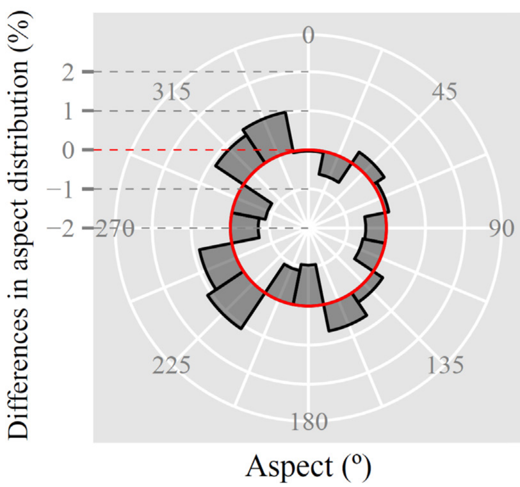


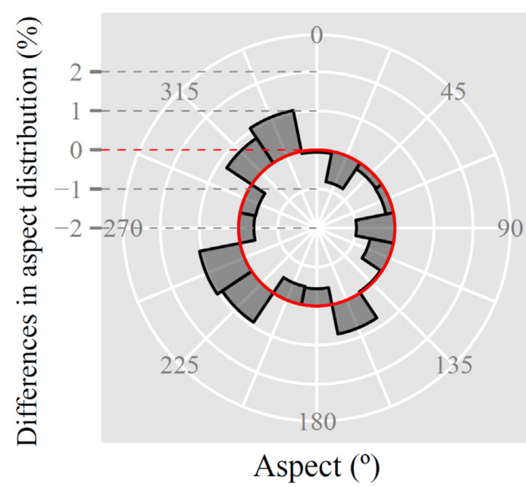
Fig. B.5. Residuals of slope differences between the original and merged DEMs. (a) Comparison to DEM_{lr}, (b) Comparison to DEM_{hr}.



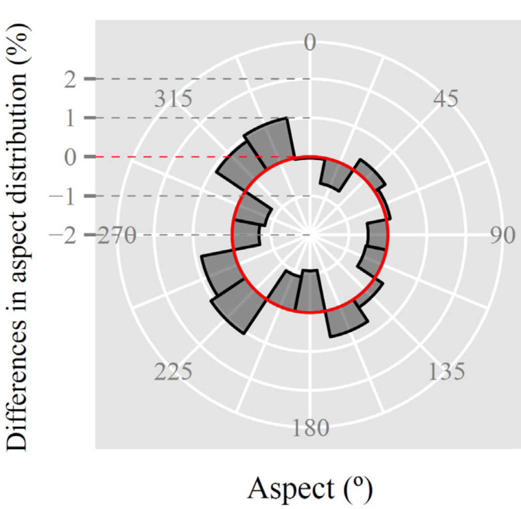
(a) **Aspect distribution of the low-resolution DEM (DEM_{lr})**



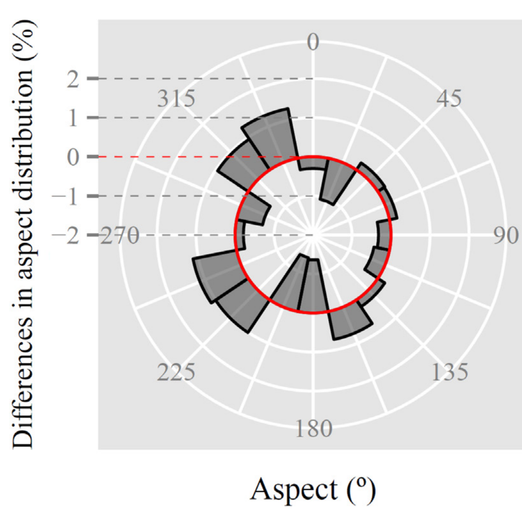
(b) `Cover` method (100% of the cells have similar aspect)



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

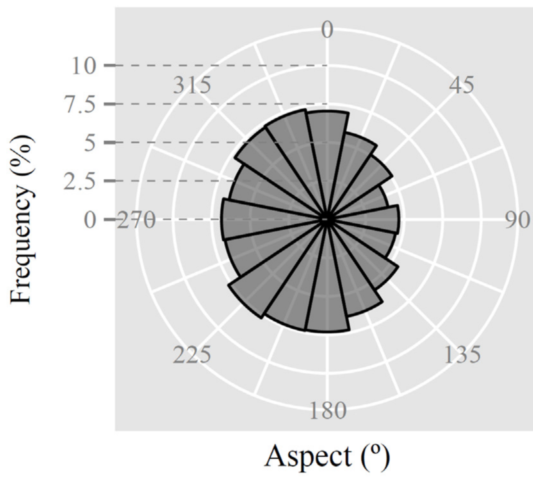


(d) `Blend` method (94.7% of the cells have similar aspect)

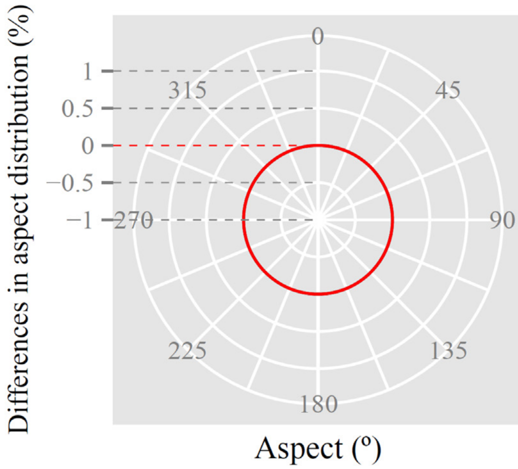


(e) `MBlend` (100% of the cells have similar aspect)

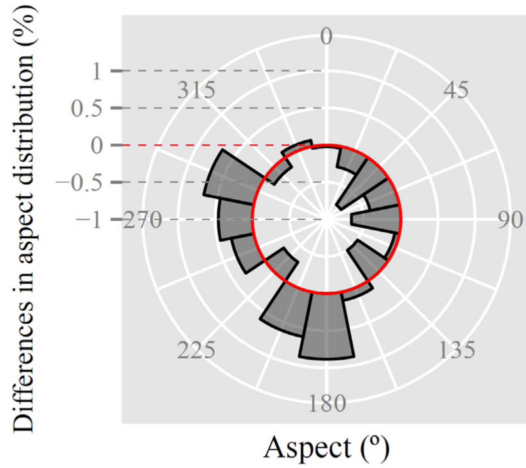
Fig. B.6. Differences of aspect distribution between the low-resolution DEM (DEM_{lr}) and merged DEMs within the 375 m buffer analysis area (Study Area 2). (a) Aspect distribution of the low-resolution DEM (DEM_{lr}), (b) `Cover` method (100% of the cells have similar aspect), (c) `Average` method (73.1% of the cells have similar aspect), (d) `Blend` method (94.7% of the cells have similar aspect), (e) `MBlend` (100% of the cells have similar aspect).



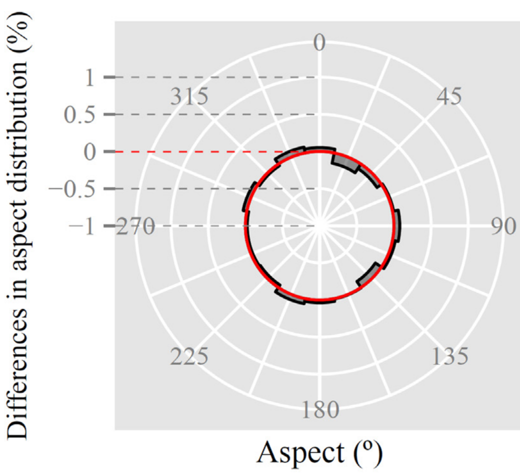
(a) **Aspect distribution of the high-resolution DEM (DEM_{hr})**



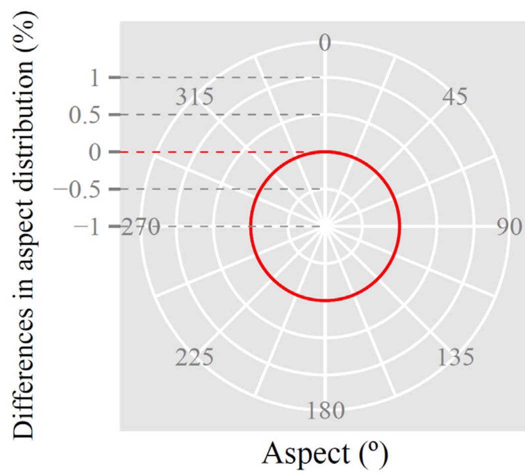
(b) Cover method (56.6% of the cells have similar aspect)



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



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



(e) MBlend (42.6% of the cells have similar aspect)

Fig. B.7. Differences of aspect distribution between the high-resolution DEM (DEM_{hr}) and merged DEMs – 375 m buffer analysis area (Study Area 2). (a) Aspect distribution of the high-resolution DEM (DEM_{hr}), (b) Cover method (56.6% of the cells have similar aspect)(c) Average method (67.6% of the cells have similar aspect), (d) Blend method (57.3% of the cells have similar aspect), (e) MBlend (42.6% of the cells have similar aspect).

Table B.3
Comparison of aspect values between original and merged DEMs.

Merging method	Coefficient of determination (R^2)	
	DEM_{lr}	DEM_{hr}
`Cover`	0.323	1
`Average`	0.477	0.553
`Blend`	0.334	0.901
`MBlend`	0.174	1

The slope range, mean and standard deviation values of the original DEMs and merged DEMs can be seen in Table B.2. 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.

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).

Fig. B.5 shows the residuals of the slope differences between the original and merged DEMs, supporting the results presented and discussed above.

As noted before, 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 for overland flow modelling. The aspect values of the merged DEMs are not significantly different from those of the original DEMs (aspect distribution differences are smaller than 2%), as can be seen in Figs. B.6 and B.7, which present the aspect distribution differences between the merged DEMs and the low-resolution DEM (DEM_{lr}) and the high-resolution DEM (DEM_{hr}). It is clear that the aspect values within the buffer analysis area are the same as the DEM_{hr} as when using `MBlend` and `Cover` (Fig. B.7e and b, respectively).

In addition to the plots, Table B.3 presents the coefficient of determination (R^2) between the aspect values of the original and merged DEMs.

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