Nov. 2010, Volume 4, No.11 (Serial No.36)
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

DEM Production/Updating Based on Environmental Variables Modeling and Conflation of Data Sources

Tomaž Podobnikar[1, 2]

1 Scientific Research Centre of the Slovenian Academy of Sciences and Arts, Novi trg 2, SI-1000 Ljubljana, Slovenia

2 Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, SI-1000 Ljubljana, Slovenia

Abstract: Availability of digital elevation models (DEMs) of a high quality is becoming more and more important in spatial studies. Standard methods for DEM creation use only intentionally acquired data sources. Two approaches which employ various types of data sets for DEM production are proposed: (1) Method of weighted sum of different data sources with morphological enhancement that conflates any additional data sources to principal DEM, and (2) DEM updating methods of modeling absolute and relative temporal changes, considering landslides, earthquakes, quarries, watererosion, building and highway constructions, etc. Spatial modeling of environmental variables concerning both approaches for (a) quality control of data sources, considering regions, (b) pre-processing of data sources, and (c) processing of the final DEM, have been applied. The variables are called rate of karst, morphologic roughness (modeled from slope, profile curvature and elevation), characteristic features, rate of forestation, hydrological network, and rate of urbanization. Only the variables evidenced as significant were used in spatial modeling to generate homogeneous regions in spatial modeling a-c. The production process uses different regions to define high quality conflation of data sources to the final DEM. The methodology had been confirmed by case studies. The result is an overall high quality DEM with various well-known parameters.

Key words: Digital elevation/terrain model, environmental variables, data quality, data conflation/integration, spatial modeling.

1. Introduction

The form of the terrestrial surface can be described as a model with continuous and usually smooth surfaces. The surfaces are defined with a finite set of elevations, measured according to the mean sea level. Such models are known as digital elevation models (DEMs) or digital terrain models (DTMs). They are basically recorded as raster layers in 2.5D, with only one attribute of elevation. There are many requirements for full 3D DEMs, especially when using very detailed laser scanning-based (LiDAR) models. The DEM is in a few words described as a raster dataset where each square cell contains an elevation value [3].

Tomaž Podobnikar, PhD, research fields: spatial analyses and modeling with geographical information systems, DEM/DTM modeling, morphometry, conflation of different qualitydata sets, palaeo-environmental modeling, natural hazards spatial modeling, historical and thematic cartography, natural and human environment impacts, data quality assessment, error simulations, Mars studies. E-mail: tomaz.podobnikar@fgg.uni-lj.si.

Typical DEM's derivatives or variables are slope, aspect, curvature, hydrological network, hill-shading and contour lines. DEM is used for wide range applications of regional planning, architecture, cartography, civil engineering, meteorology, biology, archaeology, and many more. DEMs are therefore important for various spatial analyses, modeling and visualizations.

Quality of the DEMs has been considerably increased during the last years and consequently more advanced applications aroused, e.g., for enhances morphometric analysis of floods or for environmental risks. Advanced quality assessments become more and more important in practical use.

The quality of any spatial analyses that is based on a DEM depends greatly on its geometrical and, especially, on morphological accuracy. However, due to its complexity, the primary challenge is to produce a high quality DEM according to well defined nominal ground (data model), ideally without errors and with high resolution, which is a request from most spatial data users. The DEM should be available from their point of view any time when is needed (today, now).

Nevertheless, generating of a high quality DEM is expensive and it takes considerable production time. A very demanding part of DEM production is acquisition of quality data sources [2]. Many acquisition methods – especially contemporary ones, LiDARor radar interferometry, are relatively fast and can offer quality data sources; but to get high quality DEM and to sufficiently satisfy users' requests, the production remains comparatively expensive.

It is important to find a balance between the users' demands and the capability of realization for the optimal production of DEM. The technological challenge is to use ever-larger amount of any digital data. One of the solutions is to produce a DEM from existing data sources, which are usually widely available especially for densely populated areas. Existing sources are basically acquired for applications which are not related to DEM. Many of their properties do not fulfill demands for DEM production, i.e. different geodetic points do not exactly refer to ground or contour lines are generalized considering cartographic standards. Despite the large amount of information available, such mass of data does not seem to be useful for DEM production. It might not be an obvious solution to conflate the data of morphologic and statistical (positional) inhomogeneous quality in order to obtain a high quality DEM. However, it is feasible when the best possible morphologic properties of existing data sources are applied together with the consideration of statistically obtained quality parameters (standard deviation, root-mean-square (RMS) error, max deviation, mean error, etc.). The data that contain any kind of gross error should be eliminated, also statistically better data sources are more considered for this purpose. Finally the best morphologic properties are applied.

In order to produce a DEM from various data sources a complex procedure based on modeling of environmental variables is proposed [3]. Quality parameters of potential data sources are described and applied to DEM production during the pre-processing and processing phases. The final result is outdated at the very moment it is produced, no matter how much effort is invested into DEM production. Various optimal updating modeling methods can be applied to keep homogeneous and high quality DEM.

2. DEM Production

Two approaches of DEM production that apply environmental variables are proposed. The first is DEM conflation with a method of weighted sum of sources and the second is DEM updating due to absolute and relative temporal changes. The first method is mostly used for so-called regional DEM producing, while the second is limited to small patches where different changes are observed. Environmental variables modeling as a part of DEM conflation are in greater detail explained in section 3.

2.1 DEM Conflation with Method of Weighted Sum of Sources

The goal of DEM production is to appropriately conflate (integrate) the existing data sources which are of different quality that expose their best properties. The final DEM should be an overall of better quality than any used data source.

The proposed method of weighted sum of sources with morphologic enhancement includes iterative repeated processes where the experiences and evaluations of the procedures and results acquired from previous steps provide better starting-point for each of the subsequent steps. Learning on the past experiences allows us to use improved processing parameters. Such iterative process takes more time, however it could be rationally finished within two loops. The extensive plan for DEM production and the developed methods is described in Ref. [3], where principal steps are:

- Mosaicking selected data sources to produce a principal DEM,

- weighted sum of secondary data sources,
- (geo)morphologic enhancement, and
- reference point consideration

Different aspects of quality are continuously monitored during the process following the weighted sum of data sources.

Additional products in the process of DEM production can be the automatically produced contour lines and terrain skeleton. Another benefit is acquired quality parameters; and existing spatial databases that are cleaned-up through the reduction of gross and systematic errors.

2.2 DEM Updating Due to Absolute and Relative Temporal Changes

The terrain surface (and environment in general) is constantly changing. The result is outdated DEM at the very moment it is produced. We can monitor recent local deviations and apply them to the DEM.

Natural and anthropogenic temporal changes are proposed to handle with particular methods. All of the terrain changes should be modeled individually. Many techniques are applicable for monitoring and modeling the changes, however the expected result is an updated DEM with no traces of morphologically incorrectness [4]. The corrected patches of the surface should be seamlessly conflated with the entire DEM (using mosaicking principles) and their fractal dimension should be comparable, to be homogenized with the entire DEM.

Measurements of the temporal terrain changes can be absolute or relative. The modeling of absolute changes is suitable for distinctive morphologically changed local areas due to landslides, rockfalls, quarries, watererosion, etc., while relative are appropriate for local uplifting/subsidence areas due to earthquake, mining, long term landform development, etc.

In order to apply absolute temporal changes, the area of previously modeled DEM should be cut-off the original DEM. Such an area is considered to consist of the “gross errors” (comparing with the method of weighted sum of sources where only “random errors” are considered in the modeling). After the elimination of the erroneous DEM, a new surface is mosaicked into the entire DEM.

In order to consider the relative temporal changes, we need to leave the previously modeled DEM untouched. Corrections are simply applied by adding a differential surface (corrections) to the entire DEM.

3. Environmental Variables Modeling

For the DEM production purposes, different variables recorded as continuous data surfaces are to be prepared. They demonstrate natural and anthropogenic environmental characteristics of the terrain and define high quality conflation of the DEM modeling, either according to its production (section 2.1) or updating (section 2.2). Variables are later combined and classified to particular regionalization or modeled to continuous surfaces for the particular purposes of the following DEM production phases: quality control (section 3.3), pre-processing of data sources (section 3.4), and processing the final DEM (section 3.5) [3].

3.1 Environmental Variables

Environmental spatial variables are produced through defining environmental indicators [5] that influence to particular processes of the DEM production and updating. The variables can be generated on the base of reference DEM, digitized maps or other spatial databases. Every variable used for modeling have to be statistically and visually evaluated. All of them are normalized for further common usage. The variables, produced according to natural and anthropogenic characteristics and impacts to the relevant area, are:

- genetic types (stone structure), soil types, rate of karst *K*;
- morphologic roughness *R*, that encloses: slope (inclination) *N*, profile curvature *U*, elevation *V*;
- characteristic features (terrain skeleton or morphologically enhanced areas) *O*;
- rate of forestation (woodland coverage) *G*;

- hydrological network *H*, standing water *S*;
- rate of urbanization *P*;
- other (mostly anthropogenic): transport network *T*, quarries, etc.

Another important variable (denoted as *I*) is related with a priori knowledge of involved producers (organizations), i.e. with their different interpretation of the same tasks given by subscriber. Namely, every producer has its own methodology and particular "style".

In order to produce the variables based on terrain surface characteristics (*R*, *N*, *U* and *V*), a comparatively high quality reference DEM should be modeled. It is basically modeled using the existing data sources considering preliminary knowledge of their quality and other characteristics. Preliminary knowledge is determined by considering of previous existing tests and by metadata from standardized metadatabases, e.g., according to CEN or ISO standards [8].

3.2 Spatial Modeling (Regionalization)

Spatial modeling applied for the regionalizations for DEM production and updating uses mostly relatively basic map algebra operations. The modeling produces data layers – regions or surfaces with combination of particular variables and applying operations with regard to specific demands. The geographical regions are therefore considered as classified landscape. Regions refer to more or less simple explanations of the environmental characteristics or in some cases to predictions of certain spatial characteristics. Only the variables with significant properties to a particular model are selected for the spatial modeling. The most sophisticated environmental variables are designed for quality control in the course of pre-processing of data sources (section 3.4).

3.3 Spatial Modeling for Quality Control of Data Sources, Considering Standard Regions

This modeling is used for DEM conflation from different data sources (section 2.1) and its updating due to temporal changes (section 2.2). Defining of the standard regions for quality control is an important part for further pre-processing and processing activities of the DEM production and updating. The modeling is based on the classification (regionalization). The produced data layers represent standard regions for quality control of data sources and also for the DEM as a final product.

For the beginning, the regionalization according to the terrain roughness denoted as layer RR is produced. A variable of roughness *R* is used, which is classified in four categories: flat surface (plains), low hills, hills, and mountains. Many complex methods are obtainable for such classification, but in our case the *R* is produced as a simple combination of variables *N* (slope), *U* (profile curvature) and *V* (elevation) with equation $R = N \cdot u_1 + U \cdot u_2 + V \cdot u_3$, where u_1, u_2 and u_3 are weights (ponders). They are empirically determined as $u_i = 1/3$, what is basic and most suitable solution (Fig.1). Influence of the elevation variable *V* is stronger than expected in reality, since it simulates also the roughness of the real Earth's surface–roughness have especially in the mountain areas much higher fractal dimension than it can be modeled with relatively low resolution reference DEM (i.e., 12.5 m).

Next, the standard region RN that characterizes slope

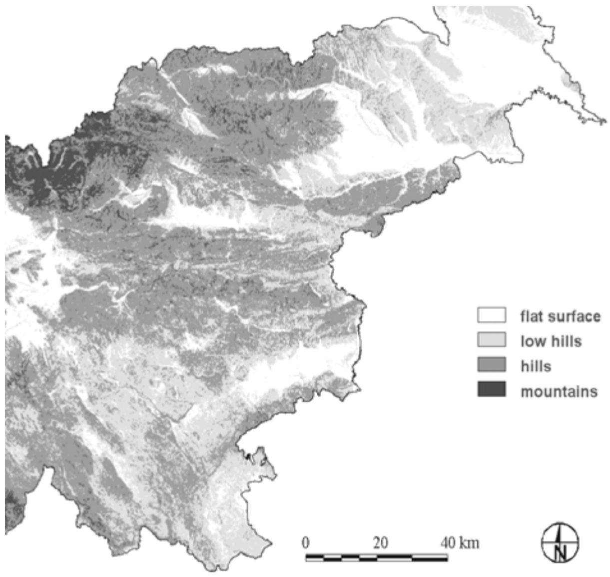

Fig. 1 Regionalization of east Slovenia to flat surface, low hills, hills, and mountains geographic units.

of the terrain is generated using variable of slope *N*. The RN is calculated from the reference DEM and then classified into three classes: 0°–5°/5°–20°/> 20°.

More complex modeling is applied to detect the standard region RO that stand for terrain skeleton, based on the characteristic features variable *O*. The RO is classified to regions of peaks, pits, saddles, ridges and valleys. A complex algorithm is based on the analysis of rasterized contour lines. The result looks very truthfully [3].

The wooded and non-wooded regions RG is to be obtained using classified satellite images (i.e., Landsat TM) or other land use (or land cover) datasets, depending on data availability and demands of their quality. The variable denotes a rate of forestation *G* is classified into categories of bushes, deciduous forest, mixed forest, coniferous forest and open areas. A binary classification for most cases of the forest and non-forest areas is appropriate.

The last regionalization RI is modeled considering the information on used methodology, where the variable *I* presents spatial distribution of particular producers of data sources.

Every individual data source later conflated to the DEM has to be statistically evaluated (i.e., with standard deviation and mean error), in our case with the reference (check) points of high and verified accuracy (i.e., with different geodetic points). The accuracy of individual data sources is evaluated according to all individual classes of the described standard regions. For example, the precision of contour lines is to be evaluated as lower in the mountain area than on the flat surface (considering standard region RR); or photo gram metrically acquired data is to be also assigned as lower quality in the forests than outside of them (considering standard region RG), etc.

3.4 Spatial Modeling for Pre-Processing of Data Sources

This modeling is used mostly for DEM conflation from different data sources (section 2.1). This modeling is basically used to distribute the weights (as part of the method of weighted sum of sources) to all potential data sources. Pre-processing is used for evaluation and improvement of the data sources quality, as well as elimination of gross and systematic errors. During this phase, different statistical parameters of data sources are determined. Data sources are also morphologically improved with hydrological analyses [3].

Quality control of data sources is divided into two tasks. The first is to eliminate gross errors from the reference points used for evaluation, and the second is using corrected reference points to evaluate the quality of potential data sources (more details in Ref. [3]). For the second task the data sources should be recorded as continuous surfaces.

Elimination of gross errors from the reference points is rather a complex task. This process is important since there are basically no perfect (errorless) reference data for testing at this stage. Moreover, randomly (or unify-distributed) distributed reference points are very rarely available. The following data potential sets can be used as reference points: fundamental geodetic network points, land registry points, database points of buildings, spot elevations, etc. In general these points are very precise and accurate, but unfortunately some of them can contain gross errors of elevations. For their quality control the (evaluated and high quality) reference DEM, as well as a reference layer (surface) RU can be used.

The proposed RU layer encloses an information on quality parameters of the reference DEM, as well as information on reference points P quality. The quality parameters are in this case potential standard deviation (as precision) of the terrain elevation.

Let's denote the quality of reference DEM by RU_0. The RU_0 is analyzed taking into account the variables of roughness *R*, rate of karst *K*, rate of forestation *G*, hydrological network *H*, standing water *S*, transport network *T*, as well as the spatial distribution of particular producers of data sources *I*. We consider that the potential precision is bigger in the rough areas (this is also applied to the karst areas that are in general rougher). The precision of data sources for DEM modeling is lower in the wooded areas. The lower precision is additionally applicable in surrounding of the hydrological network, with its sources in the changeable riverbeds. Moreover, construction of the transport network is constantly extending and its effect (dikes and trenches) is high especially in the hilly areas, which are morphologically rough. The discussed areas are in utmost cases less precisely conflated to DEM.

The layer RU_0 as a potential elevation precision is modeled from all of discussed variables. The RU_0 can be roughly evaluated with the aid of different previous quality controls, which are sufficiently regular for this purpose. Within the modeling process can be involved fuzzy logic [9] in order to indicate a degree of influence of the elevation precision surface. At the first stage, the layer RU_0 is defined only with the variable of roughness R. Further on, the obtained surface RU_0 is modified on the areas of standing water S taking into account the fact that potential precision is lower there. It is important to know and consider in the further steps common empirically developed truth that the quality of (all other) variables (K, O, G, H, T, I) to a great extent depends on the variable of terrain roughness R. For example, a potential error in wooded areas is higher than in non-wooded ones, but overall error still strongly depends on terrain roughness – therefore generally bigger error is expected in hilly, particularly in wooded hilly areas. Consequently, values of all other variables are defined as an additional correction (with different empirically defined values) of the potential standard deviation defined by RU_0. For example, the corrections in the case of the variable G are applied only within the wooded areas (values on the areas of non-wooded areas remain the same).

The final layer is calculated as $\mathrm{RU} = \sqrt{\sigma_{\mathrm{p}}^2 + k^2\sigma_{\mathrm{DEM}}^2}$, where σ_{p}^2 is variance of elevation in the points (negligible quantity) and σ_{DEM}^2 is the previously described $(RU_0)^2$ (Fig. 2). Factor k is threshold for gross error elimination, with typical values between 3 and 5. The individual tested reference point P is considered correct if it satisfied criterion $\mathrm{abs}(H_{\mathrm{p}} - H_{\mathrm{DEM}}) < \mathrm{RU}$, where H reveals elevation.

The reference points are also tested with other methods. The error is assigned with the first method, if elevations are bellow or above the terrain surface extremes on the modeled area. The second method is called robust estimation [11] which is based on statistical elimination of reference points that deviate too greatly from DEM surface taking into account the set criterion.

As the result of the first task are the errorless reference points. Considering the second task the quality of potential data sources, used in the pre-processing is evaluated, and if necessary, gross and systematic errors are eliminated.

As mentioned before, the reference points are unfortunately very rarely distributed randomly. For example, most of land registry points are on the flat areas, while they can be rarely found on the hilly areas. The obtained result may incorrectly indicate higher accuracy than it is in reality when overall accuracy of DEM is calculated, if the irregular point distribution is not considered. The procedure should consider a portion

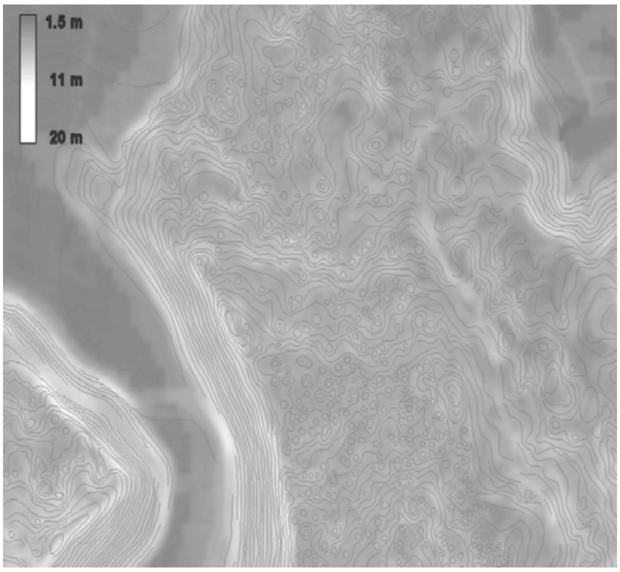

Fig. 2 Surface of predicted random error for a reference DEM (denoted as RU), with contour lines.

(area) of every class of individual standard regionalizations with regard to the number of reference points within class.

Potential data sources (considering the method of weighted sum of sources) are tested by considering the following the standard classified regionalizations:

- entire surface (as reference),
- terrain skeleton RO,
- classified roughness RR,
- classified slopes RN, and
- wooded and non-wooded regions RG.

Besides getting the quality parameters of data sources it is possible to invert the task to obtain comparable characteristics of particular geographical units. One can determine what the improvement level of the DEM production is, using the proposed parameters, e.g., to what extent the proposed parameters influence to the final DEM quality within the flat surfaces, low hills, hills, or mountains regions (regarding layer RR).

Another aspect of the spatial modeling for pre-processing of data sources is to generate surfaces of potential random error RV and systematic error RS of the data sources. Both error surfaces are modeled in a similar way, with a combination of RO, RR, RN and RG. For every category of layers, a RMS as RV, and mean error as RS is calculated. Final RV and RS are modeled by empirical factors of influence (importance) of particular regionalization to the data quality. The factors are 0.5 for RR, 0.27 for RN and 0.23 for RG. All three layers are summed up (bearing in mind the proposed factors), using map algebra operators and the RO is at the end overlaid to all of them. This resulted to smooth potential random surfaces RV and systematic errors RS.

Practically, all of the data sources should be corrected with surfaces of systematic error RS and re-tested with reference points. Tests indicated an improved quality of data sources ranging from between 30% to 60% regarding the systematic error RS. Potential random error layers of the data sources RV_i are also used as reference layers that indicate a level of permitted random error–random and gross errors of data sources are in that way distinguished.

3.5 Spatial Modeling for Processing the Final DEM

This modeling is used for DEM conflation from different data sources (section 2.1) only. The DEM processing based on weighted sum of data sources, as described. The weights are defined by potential random error layers of data sources RV_i. Higher weights refer to lower random error. Data sources are combined by calculating the arithmetic mean of them regarding corresponding weights. During the DEM processing, potential errors are decreasing by every additional source. After applying last source, the final RV is considered as the potential error of the produced DEM. More detailed description of the processing is given in the section 2 and Ref. [3].

One of the controls of the described modeling is that the final RV as a potential random error surface should be comparable with the random error, derived from tests using the DEM with reference points (RU_0). The results show relatively high rate of approximately 80% similarity of both approaches.

4. Selected Case Studies

The proposed production and updating of the DEM based on environmental variables modeling was tested and applied in several different case studies that are described.

4.1 DEM of Slovenia Conflated from Different Data Sources

The described methodology has been already fully utilized to create a high quality and cost-effective DEM of Slovenia and its surroundings with additional products (see section 2.1). The resolution of 12.5 m was selected as the most suitable. More than 25 different data sources were used. Average vertical precision is 3.2 m, while on plains it is 1.1 m, on low hills 2.3 m, on moderate hills 3.8 m, and 7.0 m in the mountain areas respectively.

The results indicate statistically, morphologically and visually high quality DEM, better than individual data sources. With conflation of various sources the statistical and morphological quality evidently increased [3].

4.2 Absolute Temporal Changes Modeling: Landslide, Quarry, Rubbish Dumps

Different data sources are used for absolute temporal changes modeling, e.g., airborne and terrestrial laser scanning (LiDAR) data, digitized historical maps, land surveying measurements, etc. As the older areas are replaced with updated, a wide range of methods for DEM production can be used. However, the methods should be suitable for principally small areas.

The first example concerns landslides and rockfalls (Fig. 3), particularly Doren landslide, northeast of Dornbirn, Vorarlberg, Austria. Repetitive airborne and terrestrial laser scanning of the landslide is employed in order to determine short-term volumetric and surface changes and its overall development [10].

Next example is quarry documentation on the base of detailed maps in scale 1:5000 and 1:25,000, or the photos, and laser scanning data. We have produced a database of quarries for entire Slovenia as side product of the conflated DEM modeling (Fig. 4). It is interesting to follow the changing of their 3D form within a certain timescale interval.

Fig. 3 Rock fall.

The last example is a DEM updating by following the shapes of rubbish dumps. An example shows a rubbish dump south-west of Ljubljana, central Slovenia, where terrestrial laser scanning was used for time intervals of one year. The changes were seamlessly updated to the original DEM (Fig. 5).

Many other absolute changes of terrain were similarly used to update the DEM of Slovenia, e.g., incorporation of detailed 3D plans of road network construction (left side of last picture in Fig. 5), changes on the area of building constructions, etc.

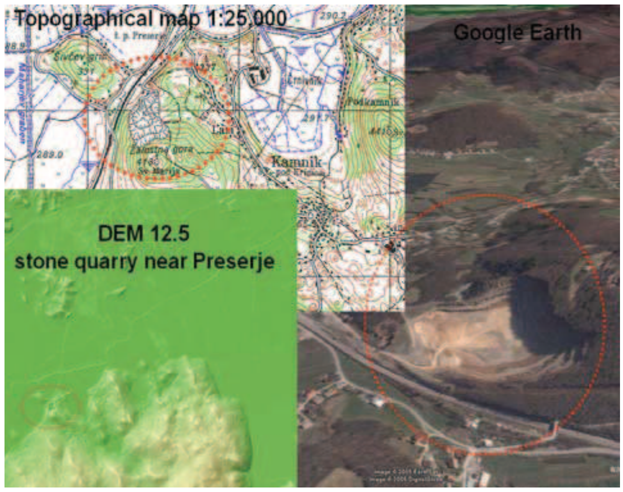

Fig. 4 Towards to the (stone) quarry database (map, DEM, orthophoto).

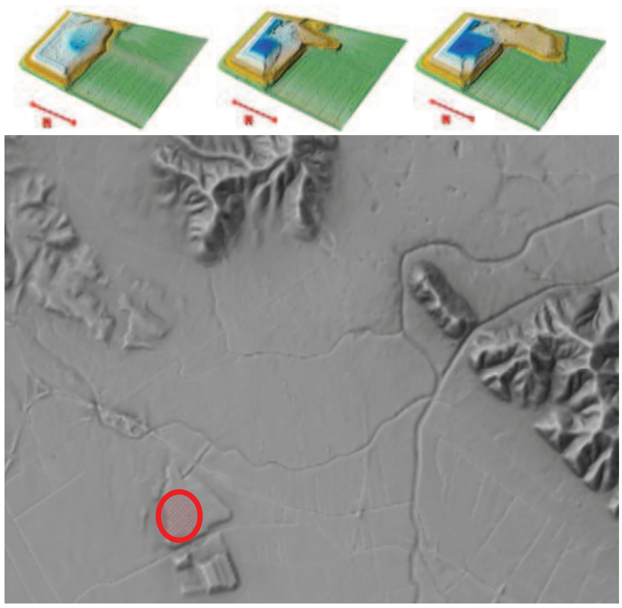

Fig. 5 Rubbish dump development in 2004, 2005 and 2006 (source: DFG Consulting, d.o.o.) and its appearance on the hill-shaded DEM, updated in 2004.

4.3 Relative Temporal Changes Modeling: Earthquake, Mining, Long Term Landform Development

Various data source are used for relative temporal changes modeling, e.g. airborne or satellite differential radar interferometry, textual notes of geologists (long term landform development), land surveying measurements, etc. All of the relative changes can be carefully conflated to the previous DEM with help of environmental modeling.

Radar interferometry techniques can be used in DEM production; nevertheless the final accuracy is relatively low. On the other hand differential interferometry can be utilized to detect small terrain surface changes and thus to update the existing DEM. With three images two interferograms can be produced and from them one differential interferogram can be computed [6].Some drawbacks are mentioned. Rough relief may present a problem due to layover and shadows. Images could be used only in valleys and not in steep slopes inclined towards the radar. Further problems can cause low coherence between the images in vegetated areas, especially during the intensive vegetation growth.

Small surface changes displacement modeling can follow the earthquakes. An example describes a relatively strong earthquake with a local magnitude of $M_{LV} = 5.6$ occurred on 12 April 1998 in western Slovenia [6]. The earthquake caused several rock falls but no direct evidence of surface torsion. Differential radar interferometry was therefore used in order to identify and possibly measure the displacement. With the basic DEM and three complex ERS radar images, taken before and after the event, three partial interferograms were created and from them the final displacement map was combined. In the area around Bovec, displacements in the order of several cm have been detected (Fig. 6). The cause of land changes could be a horizontal shift on the mountain slopes and gravel relaxation in the valley. The DEM is updating by adding the modeled continuous differential surface.

Land subsidence due to mining as anthropogenic

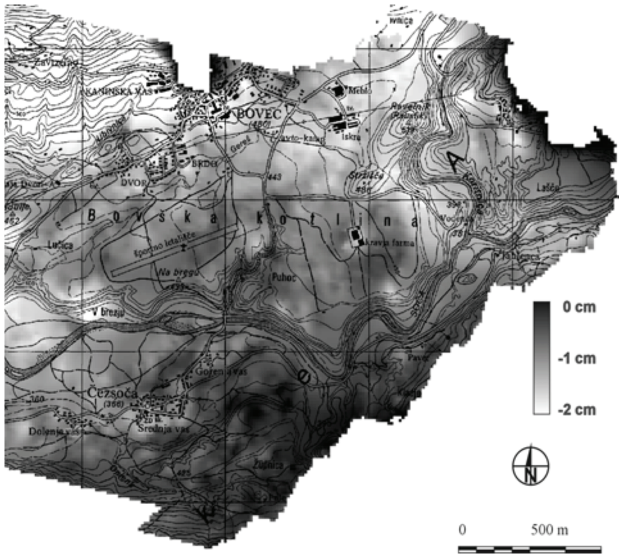

Fig. 6 Displacement caused by earthquake [6].

change was observed in the area near the Velenje coal mine in eastern Slovenia. Since the underground activity is taking place more or less all the time, we assume that the displacements are near to constant as a good approximation. The area has been observed with seven ERS-1 and 2 scans during the period from 1995 to 1999. Four differential interferograms have been produced with detectable displacements, with approximately 1 cm between individual image acquisitions. The final subsidence data layer shows a land subsidence with the rates up to 2 cm/year. The results agree with the surveying measurements in the area. Nevertheless, the geodetic network covers a larger area with just few points, while interferometry gives displacement for every pixel of 25 m resolution [6]. The described approach is similar to measurement of land subsidence deformations due to tunnel building on geologically unstable terrain. In the case of more precise measurements, the LiDAR data were used instead of differential interferometry, and static GNSS positioning with precise tacheometry [7]. Updated DEM may be calculated by adding the modeled continuous differential layers of changes considering individual time sections.

The long term landform development of relief surface modeling bases in most cases on the base of textual notes or sketches of geologists, who studied particular phenomena. The study area is surrounding by Ljubljana, central Slovenia. Supported data sets were descriptions in geological literature, oral contacts with geologist, and maps from physical geographers. The proposed method can be called reverse editing of DEM (analogue to reverse engineering). The DEM was modeled step-by-step for every historical period with points, lines and polygons that helped to fix a skeleton of the changed relief. Grid with the same resolution to the original DEM was interpolated on the base of the individual skeletons. The reliable geomorphology was kept on the base of morphologic corrections procedure modeling [3]. Finally, 81 DEMs presenting different geological periods from Oligocene until now were produced. The created DEMs are hydrologically correct, and they properly simulate riverbeds, lakes and the sea with their shores (Fig.7). The DEMs were therefore updated as combination of absolute and relative temporal changes modeling, with stress to the relative one.

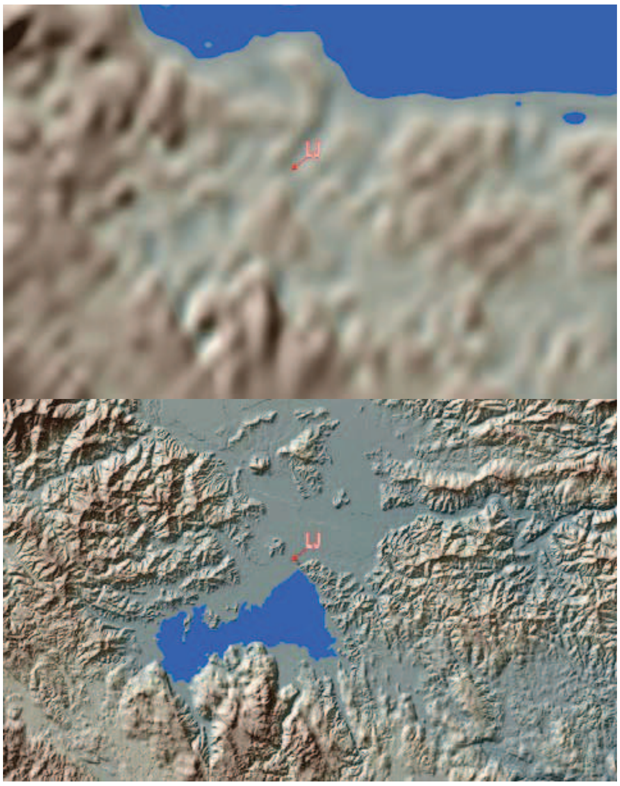

Fig. 7 Two of 81 DEMs simulating landform changes of Oligocene and Holocene (LJ is pointed to center of Ljubljana).

5. Discussion

Two distinguished approaches for the DEM production by conflation are described and tested in this paper. The first uses different data sources in order to produce the DEM of a specific temporal moment, and the second acquires and uses additional data to update the DEM as regards the temporal changes. We combined the data sources which refer to the same terrain features to produce a higher quality DEM for the first approach. The data sources could be acquired for current state or for 50 years ago, as long as they present the same features with reliable morphologic and positional accuracy.

In the areas where the relief has been recently changed, often only one (the newest) reliable data source is available; therefore all of the data sources cannot be conflated together as in the first approach. The task of this second approach was to homogenize them to the existing DEM as much as possible. It is possible to perform a temporal (cross section) series analysis which was utilized to analyze the terrain changes with the proposed approaches.

The DEMs need maintaining within the directives of further development. They can be supported by advanced technologies, based on new type of data sources (LiDAR) and advanced methods of quality control. Another problem is standardization of the DEM definition. The problem additionally arises by incorporation of more precise data sets with full 3D features that are applicable especially through LiDAR technology. Question could be: Which features are considering being part of DEM? It is widely known that the DEMs exclude vegetation, snow cover, buildings as houses and bridges, etc. [4]. There are still many uncertainties, e.g., how to present the over hangs areas (Fig. 8)? Which heights are considered for DEM; below or above of the overhangs?

A solution may lie in hybrid DEM structure that combines 2D and 3D features of relief [1]. A DEM structured on that way would be considered as more enhanced conflation for DEM creation.

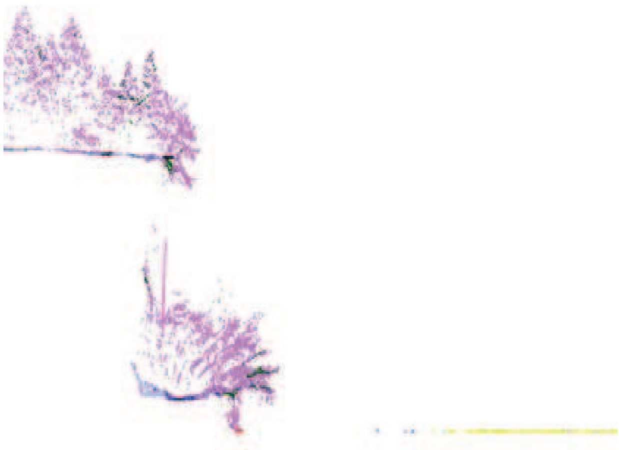

Fig. 8 Overhang of the Sava river presented with cloud of LiDAR data (source: Flaycom, d.o.o.).

Further development of the proposed DEM modeling with conflation of data sources depended on selected target resolution. The LiDAR data are comparable recorded in much higher resolution with considerable more details (typically 0.5 to 1 m), than the presented in this paper (12.5 m). It seems that the proposed methodology is not reliable. Some of the proposed methods are really not vital in the case of applying the LiDAR data. However, most of the environmental variables modeling principles can be considered for both, production (section 2.1) and updating (section 2.2). Modeling for quality control (section 3.3) can be fully applied. Spatial modeling for pre-processing (section 3.4) and for DEM processing (section 3.5) is especially important on the areas where the LiDAR is weak: forest areas (especially coniferous), rough mountain areas, and on the areas where morphologically and hydrologically very precise relief surface is needed (anthropogenic dykes/trenches, riverbeds near to buildings – houses, bridges or canals, or alluvial riverbeds). Nevertheless, the LiDAR data are strongly applicable especially on the areas, where are needs for very precise DEMs, such as alluvial areas for the floods simulation, cities, etc.

Another challenge of DEM conflation is to produce a DEM without any anthropogenic influences that resembles original relief surface. Combination of DEM conflation and updating was utilized, and during the processing the anthropogenic features were cut out from data sources.

6. Conclusion

Importance of the environmental variables modeling for high quality conflated DEM production and updating have been described and confirmed with tests. The developed modeling is significant in order to define standard regions to eliminate gross errors from the reference points used for quality control of data sources and DEM, to evaluate the quality of the potential data sources (geodetic databases), and to eliminate gross and systematic errors, as well as to control and guide DEM processing from different data sources.

The results provide statistically, morphologically and visually high quality DEM. Many additional side outputs were described, too; e.g., automatically produced contour lines and terrain skeletons. Advantage of the environmental modeling is obtaining a wide empirical knowledge on the data sources, final DEM, as well as studied environment.

It is not only vital to understand the essence of the studied problem, but it is also important to obtain the experiences to perceive and know-how to model the most significant terrain features from the available data. The developed methodology seems to be very sensible as it evaluates every potential new data source in order to find the best solution to generate better DEM.

References

[1] C. Briese, G. Mandlburger and N. Pfeifer, Airborne laser scanning - high quality digital terrain modelling, geo-sibir, in: III International Scientific Congress, Novosibirsk, Russia, 2007, pp. 79-92.

[2] P. A. Burrough and R. A. McDonnell, Principles of Geographical Systems Information Systems, Spatial Information Systems and Geostatistics, Oxford University Press, Oxford, 1998.

[3] T. Podobnikar, Production of integrated digital terrain model from multiple datasets of different quality, International Journal of Geographical Information Science 19 (2005) 69-89.

[4] T. Podobnikar, Methods for visual quality assessment of a

digital terrain model, S.A.P.I.EN.S 2 (2009) 20.

[5] T. Podobnikar, M. Schöner, J. Jansa and N. Pfeifer, Spatial analysis of anthropogenic impact on karst geomorphology (Slovenia), Environmental Geology 58 (2009) 257-268.

[6] T. Podobnikar and K. Oštir, Spatial variables modelling for high quality DTM production, Digital Earth: Information Resources for Global Sustainability, Brno, Czech Republic, 21-25 Sep., 2003, pp. 599-610.

[7] R. Vezočnik, T. Ambrožič, O. Sterle, G. Bilban, N. Pfeifer and B. Stopar, Use of terrestrial laser scanning technology for long term high precision deformation monitoring, Sensors 9 (2009) 9873-9895.

[8] S. Vogt, Knowledge-based metadata processing in an antarctic spatial decision support system, in: International Workshop on Geo-Spatial Knowledge Processing for Natural Resource Management, Varese, Italy, 2001, pp. 189-192.

[9] L. A. Zadeh, Foreword in Fuzzy Sets: Theory and Applications to Policy Analysis and Information Systems, New York, 1980.

[10] A. Zámolyi, B. Székely, G. Molnár, A. Roncat, P. Dorninger, A. Pocsai, M. Wyszyński and P. Drexel, Comparison of LiDAR-derived directional topographic features with geologic field evidence: A case study of Doren landslide (Vorarlberg, Austria), Geophysical Research Abstracts, EGU General Assembly, 2010, pp. EGU2010-9875.

[11] K. Kraus and N. Pfeifer, Determination of terrain models in wooded areas with airborne laser scanner data, ISPRS Journal of Photogrammetry and Remote Sensing 53 (1998) 193-203.