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Optimization of digital terrain model for its application in forestry

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ABSTRACT: Digital terrain model (DTM) represents a very important geospatial data type. In the Czech Republic, the most common digital contour data sources are the Primary Geographic Data Base (ZABAGED), the Digital Ground Model (DMÚ25) and eventually the Regional Plans of Forest Development (OPRL). In constructing regular raster DTM, the initial process requires interpolation between the points in order to estimate values in a regular grid pattern. In this study, constructions of DTM from the above-mentioned data were tested using several software products: ArcEditor 9.0, Atlas 3.8, GRASS 6.1, Idrisi 14.02 and TopoL 2001. Algorithm parameters can be optimized in several ways. In this sense a comparison of the first and second derivative of DTM and its real appearance in the terrain and a cross-validation procedure or terrain data measurements to compute and minimize the root mean square error values (RMSE) proved to be the most useful operations. The ZABAGED contour data provided the best results, with software specific algorithms for interpolations of contour data (ArcGIS Desktop Topo to Raster, Idrisi Kilimanjaro TIN).

Keywords: digital terrain model; geographic information system; spatial surface interpolation; software TopoL, Atlas, Idrisi, ArcGIS, GRASS; data of ZABAGED, DMÚ25, OPRL; mean square error

Digital terrain models (DTM) have been used in geoinformatics approximately since 1950 (Miller, Laflamme 1958). Since then, they have become an integral part of digital processing of spatial geographical information. In applications of geographic information systems (GIS), they provide opportunities for the modelling, analyzing and displaying of phenomena connected with topography and terrain relief. Modelled areas are often very extensive, however the features with longitudinally unruffled course but in a vertical direction the terrain area breaking sharply on them are the major problem. A mathematical characteristic of these singularities is discontinuity of the function or discontinuity of its derivation.

The selection of data sources, as well as the method of collecting terrain data and their area location, influences significantly the quality of resulting DTM. Primary source data are acquired by surface measurements (Surveying, Global Positioning System) or by Remote Sensing technologies (photogrammetry, radar and laser scanning). Secondarily, the existing digital data (Primary Geographic Data Base, Digital Ground Model, etc.) can be used or we can digitize analogue bases for DTM. The accuracy of these diagrammatic data is set down by the Standard ČSN 01 3410 (for the construction and maintenance of basic and special-purpose maps of large scales). In the forestry sector, these problems are related to § 5 of Decree No. 84/1996 of the Ministry of Agriculture of the Czech Republic, about forest management planning, yet it does not consider the accuracy of diagrammatic data. Various procedures which enable to increase the accuracy of created DTM are very often combined.

DTM is basically developed on the basis of selected data representation. The raster model is seen in two variants. The first one considers a cell (pixel) as a facet enclosed by four points of a raster net, each of which can have a different grid. The resulting model therefore consists of warped quadrangles. The second one considers a cell (pixel) as an object representing a rectangular facet integrally and the assigned value represents a grid attribute for the whole surface of a cell (pixel) – this variant is most frequently used in raster oriented GIS (Kraus 2000). Elementary facets of a polyhedric model are triangles which adjoin to each other, thus creating a polyhedron adjoining to the terrain. The polyhedron vertexes are points on a terrain area; the area interpolation is usually done linearly triangle by triangle. This approach, denoted as a triangulation or Triangulated Irregular Network (TIN), is currently the most widespread with vector oriented GIS. A plate model has many features common to the polyhedric model. The terrain is also divided into smaller surfaces which do not have to be only flat, they can be curved somehow. The areas described by polynomial functions, which concur so fluently to guarantee a continuity of derivations to a certain advance system, are used most frequently.

Interpolation in the process of terrain modelling makes for the calculation of values in places where they were not measured. Most frequently it is the calculation of a grid for the given point or pixel, the calculation of location at the interpolation of contour lines or the change of resolution (resampling), in some cases the change of data structure. The problem covers generally applicable statistic procedures and methods which are specifically modified for the need of relief terrain modelling. The most frequently applied methods include Inverse Distance Weighting (IDW) method, triangulation with linear interpolation, spline methods, radial function methods, kriging and conditional stochastic simulation.

Much valuable information in the form of attributes related to the surface of a real terrain can be acquired by the interpretation (analysis) of terrain models. These analyses can proceed on two levels, though they occur in combination more frequently. Either it is a visual (graphic) interpretation or purely quantitative analysis, and outputs can be used in other components of GIS or they represent an input into other models (e.g. hydrological or erosive). Evans (1972) divided the analysis of geomorphometric parameters into general geomorphometrics (slope, aspect, curvature) and specific geomorphometrics (topographic shape classification, flow direction, watershed and viewshed analysis).

The use of DTM is very extensive, as we can already see from the possibilities of the analysis. Forestry belongs to the fields that deal with renewable natural resources management and terrain characteristics markedly influence individual components of forest ecosystems. DTM can have their use partly in generally shaped disciplines focused on forestry (forest pedology, typology, constructions, ameliorations, etc.) and partly in forest management planning itself. It is therefore possible to model soil characteristics on the basis of DTM (e.g. soil moisture and transport of sediments), hydrological characteristics (e.g. flow direction and accumulation, watershed, erosion hazard) and climatic characteristics (e.g. temperature and insolation parameters). In the field of the forest management planning, many functions for the effectiveness and accuracy of work are suggested:

– measurement of stand height on the basis of detailed DTM and aerial stereophotogrammetric images,

– orthorectification of aerial and satellite images for the elaboration of forest management plans (LHP),

– forest road network optimization and subsequent mass calculations for construction,

– background data for calculations of hazardous factors of erosive exposure of forest soils,

– background data for terrain classifications in logging,

– modelling of climatic parameters correlating with the altitude and terrain shape (frost basins, anemo-orographical systems, etc.),

– background data for a modelling of the spread of abiotic and biotic harmful factors (fire, pollutants, animal pests, etc.).

DTM is also the basic technological component of a digital landscape model (DLM) recording in a simplified form structural and dynamic features of a chosen segment of the landscape sphere of the Earth. Manipulation with this model is done on the basis of user's instructions into an integrated database through a knowledge base, which is then able to direct the creation of a sequence of situations up to the achievement of a predefined stage. DLM enables to detect areas in a landscape which fulfil defined ecological, economic and social criteria.

MATERIAL AND METHODS

DTM were tested in an experimental locality in the territory of the Křtiny Training Forest Enterprise Masaryk Forest (ŠLP Křtiny), which is a special-purpose institution of Mendel University of Agriculture and Forestry Brno and serves its Faculty of Forestry and Wood Technology to provide pedagogical, research, pilot and testing projects. The experimental locality is situated in the southwest section of ŠLP Křtiny, in the northeast of Soběšice village. It comprises of a complex of sections 62 to 68 in forest district 10 – Vranov. The area of this complex is 225 ha and belongs to cadastral area No. 370200404 – Soběšice and No. 370300401 – Bílovice nad Svitavou. The altitude ranges from 250 m above sea level in the southeast section of the valley of the Melatín stream up to

430 m above sea level in the middle section of the locality. The area is shaped by a ridge of an oblong shape in the north-south direction, whereas the western and eastern slopes are furrowed by numerous dry valleys and there is a section which is separated by a valley in the west-east direction in the south.

The base for DTM creation in the selected area was the already existing digital geodata. Only vector data were used from Regional Plans of Forest Development (OPRL) data, concretely thematic blocks VRS.BLK and VRX.BLK, which contain spot heights in full metres and contour lines with the interval 20 m (including line symbols for detritus and rocks and a textual description of the altitude in the block VRX). OPRL digital data for the experimental locality in Forest Natural Area No. 30 (Drahanská vrchovina) were compiled by Forest Management Institute in Brandýs nad Labem, Brno branch, with the effect from 1. 1. 2000 to 31. 12. 2019. An important fact is also that the contour lines are disconnected at the places where the textual description of the altitude occurs. Diagrammatic data from the Primary Geographic Data Base (ZABAGED), which are distributed on map sheets Basic Maps of the Czech Republic 1:10,000, were the second source. The experimental locality can be found on sheets (Brno) 24-32-15 and 24-32-20. Digital hypsography is provided in DGN format and contains only the contour lines in the variable interval 2, 4, 6, 8 and 10 m (24-32-20) or 5 and 10 m (24-32-15). An important fact is that the contour lines are disconnected at the places of terrain singularities (ravines, cuttings, etc.), which means that the hypsographic data is missing because a symbol without height attribute was in the source analogue map. The data were compiled by the Czech Office for Surveying, Mapping and Cadastre. Diagrammatic data from the Digital Ground Model (DMÚ25) were the last source. These data contain only the contour lines in the interval 5 m and unlike ZABAGED data, these lines are uninterrupted. The experimental locality can be found on sheets M-33-106Ab and M-33-106Ad. The data format is ESRI ShapeFile and the data were compiled by the Military Office for Geography and Hydrometeorology. From all these data it was necessary to choose the area of experimental locality and to realize conversion for the access into chosen software products. The system of coordinates Unified Trigonometric Cadastral Network (JTSK) and the elevation system Baltic after Equation (Bpv) were used for all data.

The control data were located by a combined procedure with the use of GPS technology and geodetic procedures. The interpolated height in resulting raster models represents the value of the whole pixel with the given size (area), whereas the resolution of the resulting DTM with the pixel size 5 × 5 m was selected. The position component of control pixels was located with GPS Trimble GeoExplorer XT, namely by the code measurement by a static method with 10-minute observation length (120 records with 5-second interval). The postprocessing method of corrections was used for the specification of measured points after termination of measurements, applying data from a permanent GPS station in TUBO point situated at an appropriate distance ca. 7 km from the experimental locality. The data are provided by the Faculty of Civil Engineering (University of Technology Brno) freely to download on web sites. Measured data processing was done in GPS Pathfinder Office 3.00, which allows both working with the measured data and their correction and the export into common vector formats. The error in the accuracy of determination of the position component after corrections did not exceed 2 m, which is absolutely suitable in terms of the pixel size. Unfortunately, it is not possible to reach the accuracy usable for control in the height component because it was verified that this error made a double to quadruple of the position measurement inaccuracy. Therefore it was necessary to locate the height component in control points in a levelling way with the usage of the data of the nearest trigonometric points by the method of geometric levelling from the centre using the instrument Topcon AT-64 with a levelling stick and an underlay. The error in the accuracy of determination of the height component did not exceed 10 cm, which is fully sufficient in terms of terrain characteristics in forest ecosystems. In total 250 points were located uniformly over the experimental locality. The points were recorded in the format of a vector point area with an attached database. This vector file was transferred into a raster form as necessary with the pixel size appropriate to DTM created for further analysis.

DTM were created in several chosen software products to evaluate the quality of used interpolations, specifically TopoL 2001 program (traditional and massive usage in forestry), Atlas 3.8 program (classical Czech product for engineering applications), ArcEditor 9.0 program with extensions Spatial and 3D Analyst (considering its worldwide prevalence) and from among the representatives of less used but good-quality software, the products Idrisi 14.02 Kilimanjaro and GRASS 6.1. Interpolation procedures used for creating DTM fundamentally influence the quality of resulting models and become the basic characteristic of created facets.

Generally, the interpolation evaluation was divided into two stages. In the first stage, the most suitable interpolation procedure was chosen from among the possibilities offered by software, and subsequently its parameters were optimized to reach the best interpolation effect. The interpolation quality was evaluated on the basis of comparison with input data. The contour lines were generated from the created model, having a half interval of the input data, and the accuracy by which they describe a terrain among the contour lines of original data was evaluated. The other method was the control on the first and second surface derivations. The errors in interpolations of local minimums and maximums can be detected by slope and aspect, and along with the surface curvature, their logical occurrence in a terrain can be controlled. The size of standard deviation of interpolated surfaces together with a cross-validation procedure was evaluated from statistical devices. In the case of geostatical methods, a great advantage was the possibility to evaluate variances on the whole coherent surface.

While in the first stage the control was done only on the basis of input data which are considered to be fundamental and correct, the second stage of control was focused on quantification of the accuracy of the created DTM, including the identification of possible errors in source data. This step was realized on the basis of check measurement. The accuracy for the experimental locality was evaluated by quantification of the root mean square error (RMSE) of elevation. This value represents an interval the real deviation between the interpolation surface value and the check measurement does not exceed with certain probability. It is then generally valid, the smaller the RMSE, the more solid the appropriate interpolation. Rasters provided the best results of interpolation, while using the mentioned input data and individual programs after the first stage control were chosen. On the basis of data from the check measurement, the calculation of RMSE was done. The vector point field of check height measurement was transferred into raster representation (pixels were matched both positionally and dimensionally with rasters of interpolated DTM) along with the creation of a mask of this raster (all pixels of the original point field were given the value 1). This mask eliminated the values in interpolated DTM except the points of the check measurement and consequently both rasters were subtracted, whereby the difference between the value of the interpolated surface and the value from the check measurement in a given place was obtained. The differences Δh (in the attribute of a given pixel) were exported to ASCII file (by means of module XYZIDRIS in Idrisi Kilimanjaro) and the value of the mean square error was calculated (in Microsoft Excel program) according to the formula:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta h_i)^2} \qquad (1)$$

where: N – the number of point elements, in this case 250.

RESULTS AND DISCUSSION

The most accurate sources for DTM construction are geodetic measurements, but their demands on

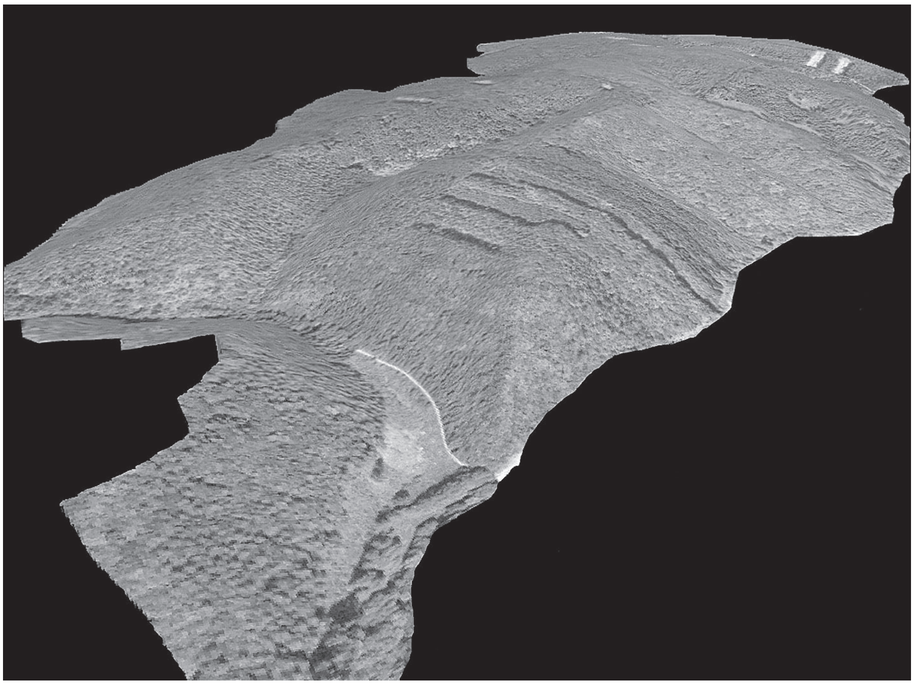

Fig. 1. 3D visualization of the experimental locality

Table 1. RMSE values of interpolated surfaces in ArcEditor 9.0 software

Algorithm	RMSE value (m)		
	ZABAGED	DMÚ25	OPRL
IDW (power = 2, min. points = 24, barrier lines)	3.78	6.04	11.80
Spline (regularized, τ = 0.01, min. points = 24)	4.69	6.13	12.86
Spline (tension, φ = 10, min. points = 24)	4.27	7.24	11.84
Topo to Raster	1.63	2.84	8.87
TIN	3.39	5.87	11.69
Ordinary kriging (minimum variability)	3.38	5.74	11.85

instrument equipment and skilled staff are high, as well as the time consumption of measurements. Fako (2000) gave a particular example and stated that the accuracy of height determination in DTM varied from ± 0.03 to 0.35 m. Higher effectiveness can be achieved by the possible usage of GPS technologies for a ground measurement with similar demands on instrument equipment. Even though the progress in this area is very fast, yet it is not possible to use the measured height component sufficiently due to the variation of its accuracy. The quality of GPS measurement can also be negatively influenced by the presence of a stand which rather limits the possibilities of usage in forestry. Remote Sensing is another important data source, mainly the results of stereophotogrammetric analysis, and laser data and radar scanning. At present, stereophotogrammetry is mostly used to acquire height data for creating contour lines in large areas. The accuracy of these data is limited by direct visibility of the terrain surface, and mainly the height of vegetation cover and its continuity manifest adversely here. Fako (2000) reported a particular example and stated that the accuracy of height determination in DTM varied from ± 1.21 to 1.37 m in these methods. A qualitative shift in the effective collection of height data (the centimetre accuracy order) would be the routine setting of laser scanning technology. This method makes it possible to collect data for large areas, similarly like stereophotogrammetric methods, but is not limited by the vegetation cover in the landscape.

Already existing digital diagrammatic data were used for practical application. The aim was to evaluate the accuracy of created DTM because this type of data is mostly applied in DTM applications in practice. These data have two crucial negatives. They do not contain the values of local maximum and minimum (i.e. spot heights on peaks, ridges and also in valleys) and the data are irregularly arranged in layers depending on the terrain shape, which often leads to the absence of height identifications (typically in the longitudinal axis of ridges and valleys).

The quality of the created experimental DTM conveyed by the quantification of RMSE value corresponds to presuppositions proceeding from the evaluation of the quality of used input data. ZABAGED data proved to be the most accurate, with accuracy expressed by the RMSE value in the interval ± 1.63 to 5.60 m, then DMÚ25 data, with accuracy expressed by the RMSE value in the interval ± 2.84 to 7.40 m, and finally OPRL data, with the accuracy expressed by the RMSE value in the interval ± 8.87 to 14.08 m. This corresponds to the characteristics of input data. ZABAGED data are an equivalent of maps at the scale 1:10,000, while DMÚ25 data are related to the scale 1:25,000 at the contour interval 5 m, and the least accurate data OPRL have the contour interval 20 m. These characteristics (insufficient and irregular distribution of height identifications for interpolation) negatively influenced the accuracy of created models. Tuček and Majlingová (2004) realized the same evaluation for hypsography forest

Table 2. RMSE values of interpolated surfaces in Idrisi 14.02 Kilimanjaro software

Algorithm	RMSE value (m)		
	ZABAGED	DMÚ25	OPRL
INTERPOL (distance weight exponent = 2)	5.60	6.83	14.08
INTERCON (rasterized contours)	5.52	7.40	13.44
TIN (breaklines, parabolic B/T removal)	1.68	3.01	9.12
Ordinary kriging (minimum variability)	3.23	5.83	11.71
Ordinary kriging (maximum variability)	3.56	5.96	12.44

Table 3. RMSE values of interpolated surfaces in other software

Algorithm	RMSE value (m)		
	ZABAGED	DMÚ25	OPRL
TopoL TIN (Delaunay triangulation)	4.02	5.95	11.89
TopoL TIN (Delaunay triangulation with breaklines)	3.64	6.01	11.51
Atlas TIN (with breaklines)	2.56	4.38	10.88
GRASS module v.surf.rst (tension = 30, smooth = 0.2)	4.07	5.87	12.16

map data (analogy of OPRL data) in their own experimental locality and the calculated value of RMSE was in the interval ± 12.71 to 17.35 m.

Considering the obtained results, the algorithms can be divided into types using TIN structures and types using defined functions. It can generally be said that TIN structures are a very appropriate device for creating DTM surfaces. Their algorithm is multiplied faster than the interpolation by other functions and we can effectively incorporate terrain singularities into the TIN structure in a form of obligatory edges (including the definition of obligatory edges of contour lines) and thus control the interpolation in individual triangles (when working on high volume data, it is a very demanding activity). A crucial disadvantage is the impossibility of interpolations of local maximum and minimum if these values are not contained in source data. Contour lines provide a typical case when in the absence of spot heights reliable DTM cannot be created, mainly on ridges and in valleys. The usage of other algorithm modifications, such as inserting parabola and retriangulation (module TIN Idrisi Kilimanjaro) is the solution.

The second group comprises algorithms which use variously defined functions for the estimation of values. In this connection it is to note that their usage for DTM creation is only one of the possibilities because they are used mainly for interpolation on a general level. Real terrains have many specific features and reliance that cannot be influenced without sufficient possibilities of modification of algorithm parameters. An example of this statement can be the relatively simple method IDW which in INTERPOL module (Idrisi Kilimanjaro) presents considerably worse results than IDW algorithm constructed practically in the same way in ArcGIS Desktop that allows to influence many parameters (Tables 1 and 2).

Further, it is possible to use instruments of geostatics for DTM processing. Geostatic methods have rapidly expanded in recent years and can be used for the interpolation of DTM values successfully. They provide many variants and a great advantage is information about the accuracy of interpolation at each point of the created surface. Unfortunately, these instruments require sufficiently skilled staff (statistical analysis of input data, trend removing, analysis and modelling of variability, model designing and choice of a suitable variant of calculation including correct interpretation of results are realized), without them the results are considerably worse or useless.

Various methods of spline functions or radial functions are an acceptable compromise. These approaches are easy to manage even for an average user and thanks to algorithm features errors in the interpolation of local minimum and maximum in the absence of the values of input data can be appropriately minimized. The quality of created DTM is very versatile depending on setting the parameters (tension and smooth factors in spline algorithms), or whether the degree of smoothing a model for visualization or maximal accuracy when keeping input data is preferred (see Tables 1 and 2). The impossibility of modelling any singularity (coherently smoothed areas are created) is also a disadvantage which markedly limits engineering applications of DTM.

In connection with the results obtained by the application of chosen methods of DTM interpolation in the experimental locality (and depending on input data), the usage of specifically prepared algorithms seems to be the most suitable. The best results were obtained by Topo to Raster module. This algorithm uses a modification of the spline method and hydrological characteristics for creating a maximally accurate DTM and also allows its further specification implementing subsidiary data into the model (spot heights and hydrological network). It is also possible to obtain good results in the TIN structure if we can eliminate the problems of the absence of spot heights and if we can control the quality of triangulation (Idrisi TIN).

The aim of this study was to identify the real achievable accuracy of DTM from the most frequently used data because nowadays most models are generated by software instruments for GIS and their authors do not often have sufficient knowledge of these problems and do not evaluate the accuracy of the models. It is important to point out that the obtained results exceed the criteria of the above-mentioned accuracy classes ČSN 01 3410 with the exception of values obtained by the interpolation of ZABAGED data in Topo to Raster module (Tables 1 to 3).

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Optimalizace digitálního modelu terénu pro aplikace v lesnictví

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ABSTRAKT: Digitální modely terénu (DMT) tvoří velmi důležitý typ geoprostorových dat. V České republice jsou pro DMT nejčastěji využívána digitální vrstevnicová data ze Základní báze geografických dat (ZABAGED), Digitálního modelu území (DMÚ25) a event. z Oblastních plánů rozvoje lesů (OPRL). Pro konstrukci rastrových DMT je zapotřebí provést interpolaci vstupních bodů k dosažení všech hodnot pravidelného rastru. Práce byla zaměřena na konstrukci DMT z uvedených dat při využití několika softwarových produktů: ArcEditor 9.0, Atlas 3.8, GRASS 6.1, Idrisi 14.02 a TopoL 2001. Parametry algoritmů byly optimalizovány několika způsoby. Byly porovnávány první a druhé derivace povrchu a jejich reálný výskyt v terénu a dále bylo využito křížové validace nebo výpočtu a minimalizace střední kvadratické chyby. Nejlepších výsledků bylo dosaženo při použití dat ZABAGED a specificky připravených algoritmů pro interpolaci vrstevnicových dat (ArcGIS Desktop Topo to Raster, Idrisi Kilimanjaro TIN).

Klíčová slova: digitální model terénu; geografický informační systém; prostorová interpolace dat; software TopoL, Atlas, Idrisi, ArcGIS, GRASS; data ZABAGED, DMÚ25, OPRL; střední kvadratická chyba

Digitální modely terénu (DMT) jsou používány v geoinformatice zhruba od roku 1950 (Miller, Laflamme 1958). Od této doby se staly nedílnou součástí digitálního zpracování prostorových geografických informací. V aplikacích geografických informačních systémů (GIS) poskytují příležitosti pro modelování, analyzování a zobrazování úkazů souvisejících s topografií a s reliéfem terénu. Výběr datových zdrojů – stejně tak jako metoda sběru terénních dat a jejich plošné rozmístění – má významný vliv na kvalitu výsledného DMT. Primární zdrojová data jsou získávána pozemním měřením nebo technologiemi dálkového průzkumu Země. Sekundárně lze pro DMT využít již existující digitální data nebo digitalizovat analogové podklady. Přesnost těchto výškopisných dat upravuje norma ČSN 01 3410 (pro tvorbu a údržbu základních a účelových map velkých měřítek). V oblasti lesnictví se této problematiky dotýká § 5 vyhlášky Ministerstva zemědělství České republiky č. 84/1996 Sb., o lesním hospodářském plánování, avšak nijak neřeší přesnost výškopisných dat.

DMT je v podstatě tvořen na základě zvolené datové reprezentace pomocí interpolačních procedur. Nejčastěji se jedná o výpočet výšky pro zadaný bod nebo pixel, výpočet polohy při interpolaci vrstevnic anebo změnu rozlišení (resampling), případně změnu datové struktury. Problém se tedy dotýká obecně aplikovatelných statistických postupů a metod, které jsou specificky upravovány po potřeby modelování reliéfu terénu. Interpretací (analýzou) modelů terénu je možné získat řadu cenných informací ve formě atributů, vztahujících se k povrchu reálného terénu.

DMT byly testovány na experimentální lokalitě na území Školního lesního podniku Masarykův les Křtiny (ŠLP Křtiny), který je účelovým zařízením Mendelovy zemědělské a lesnické univerzity v Brně. Experimentální lokalita se nachází v jihozápadní části ŠLP Křtiny, severovýchodně od obce Soběšice, tvoří ji komplex oddělení 62 až 68 v polesí 10 – Vranov.

Základem pro vytvoření DMT na zvoleném území byla již existující data – digitální vektorová data Oblastních plánů rozvoje lesů (OPRL), Základní báze geografických dat (ZABAGED) a Digitálního modelu území (DMÚ25).

Kontrolní data byla zaměřena kombinovaným postupem s využitím technologie GPS a geodetických postupů. U výsledných rastrových modelů interpolovaná výška reprezentuje hodnotu pro celý pixel o daném rozměru (ploše), přičemž bylo zvoleno rozlišení výsledných DMT o velikosti pixelu 5 × 5 m. Polohová složka kontrolních bodů byla zaměřena pomocí GPS Trimble GeoExplorer XT, a to kódovým měřením statickou metodou při délce observace 10 minut (120 záznamů při intervalu 5 s). Pro zpřesnění měřených bodů byla využita metoda korekcí po skončení měření (postprocessing) s využitím dat z permanentní GPS stanice na bodu TUBO, situované ve vhodné vzdálenosti asi 7 km od experimentální lokality. Chyba v přesnosti určení polohové složky po korekcích nepřekročila 2 m, což je z hlediska velikosti pixelu zcela vyhovující. Výškovou složku bylo nutné na kontrolních bodech zaměřit nivelačně při využití údajů z nejbližších trigonometrických bodů metodou geometrické nivelace ze středu za použití přístroje Topcon AT-64 s nivelační latí a podložkou. Chyba v přesnosti určení výškové složky nepřekročila 10 cm, což je vzhledem k vlastnostem terénu v lesních ekosystémech plně dostačující. Celkem bylo rovnoměrně zaměřeno po experimentální lokalitě 250 bodů, které byly zaznamenány ve formátu vektorového bodového pole s připojenou databází.

Pro vyhodnocení kvality použitých interpolací byly DMT vytvořeny v několika vybraných softwarových produktech. Jednalo se o programy TopoL 2001 (tradiční a masivní využití v lesnictví), Atlas 3.8 (klasický český produkt pro inženýrské aplikace), ArcEditor 9.0 s extenzemi Spatial a 3D Analyst (vzhledem k jeho celosvětovému rozšíření) a ze zástupců méně využívaného, ale kvalitního softwaru se jednalo o produkty Idrisi 14.02 Kilimanjaro a GRASS 6.1.

Obecně bylo hodnocení interpolace rozděleno do dvou fází. V první fázi docházelo k výběru nejvhodnější interpolační procedury z možností poskytovaných softwarem a následně k optimalizaci jejích parametrů pro dosažení nejlepšího efektu interpolace. Využívalo se zde hodnocení kvality interpolací na základě porovnání se vstupními daty. Z vytvořeného modelu byly generovány vrstevnice s polovičním intervalem, než měla vstupní data, a hodnotila se přesnost, s jakou vystihují terén mezi vrstevnicemi původních dat. Další metodou byla kontrola na prvních a druhých derivacích povrchu. Sklonem a expozicí lze odhalit chyby v interpolacích lokálních minim a maxim a současně s křivostí povrchu kontrolovat jejich logický výskyt v terénu. Ze statistických nástrojů byla hodnocena velikost směrodatné odchylky interpolovaných povrchů současně s křížovou validací.

Zatímco v první fázi se prováděla kontrola pouze na základě vstupních dat, která se považují za zásadní a správná, tak druhá fáze kontroly se zaměřila na kvantifikaci přesnosti vytvořeného DMT včetně identifikace možných chyb ve zdrojových datech. Tento krok byl realizován na základě kontrolního měření. Pro experimentální lokalitu byla přesnost hodnocena kvantifikací střední kvadratické chyby (RMSE) výšky. Obecně potom platí, že čím je střední kvadratická chyba menší, tím je příslušná interpolace spolehlivější. Pro vlastní kontrolu byly vybrány rastry DMT, které poskytovaly nejlepší výsledky interpolace při použití zmíněných vstupních dat a jednotlivých programů po provedení první fáze kontroly.

Kvalita vytvořených experimentálních DMT, vyjádřená kvantifikací střední kvadratické chyby, odpovídá předpokladům, vycházejícím z hodnocení kvality použitých vstupních dat. Jako nejpřesnější se ukázala data ZABAGED s přesností vyjádřenou hodnotou RMSE v intervalu ± 1,63 až 5,60 m, potom data DMÚ25 s přesností vyjádřenou hodnotou RMSE v intervalu ± 2,84 až 7,40 m, a nakonec data OPRL s přesností vyjádřenou hodnotou RMSE v intervalu ± 8,87 až 14,08 m.

Vzhledem k dosaženým výsledkům lze algoritmy rozdělit na typy využívající nepravidelnou trojúhelníkovitou síť (TIN) a na typy využívající definovaných funkcí. Obecně lze říci, že pro vytváření povrchů DMT jsou TIN struktury velmi vhodným nástrojem. Jejich algoritmus je mnohonásobně rychlejší než interpolace jinými funkcemi a do struktury TIN lze efektivně začlenit singularity terénu v podobě povinných hran (včetně definice povinných hran linií vrstevnic), a tím kontrolovat interpolaci u jednotlivých trojúhelníků (při práci na rozsáhlých datech se však jedná o značně náročnou činnost). Zásadní nevýhodou je nemožnost interpolací lokálních maxim a minim, pokud tyto hodnoty nejsou obsaženy ve zdrojových datech. Typickým případem jsou právě vrstevnice, kde v případech, kdy chybějí výškové kóty, nelze vytvořit spolehlivý DMT (zejména na hřbetech a v údolích). Řešením je použití dalších modifikací algoritmu, jako je např. vkládání paraboly a retriangulace (modul TIN Idrisi Kilimanjaro).

Druhou skupinou jsou algoritmy, které pro odhad hodnot využívají různě definovaných funkcí. V této souvislosti je vhodné uvést, že jejich použití pro tvorbu DMT je jen jednou z možností, protože se využívají především k interpolaci v obecné rovině. Reálné terény totiž mají řadu specifických vlastností a závislostí, které nelze bez dostatečných možností modifikace parametrů algoritmů ovlivňovat. Vhodným kompromisem jsou potom různé metody minimální křivosti či radiálních funkcí. Tyto přístupy zvládá i průměrný uživatel a díky vlastnostem algoritmů lze vhodně minimalizovat chyby v interpolaci lokálních minim a maxim u chybějících hodnot vstupních dat. Nevýhodou také zůstává nemožnost modelování jakékoliv singularity (jsou vytvářeny souvisle vyhlazené povrchy), což výrazně omezuje inženýrské aplikace DMT.

V souvislosti s výsledky dosaženými při aplikaci vybraných metod interpolace DMT na experimentální lokalitě (a v závislosti na vstupních datech) se jako nejvhodnější prokázalo využití specificky připravených algoritmů. Nejlepší výsledky byly dosaženy pomocí modulu Topo to Raster. Tento algoritmus využívá modifikace spline metody a hydrologických charakteristik k vytvoření maximálně přesného DMT a umožňuje i jeho další zpřesnění zavedením pomocných dat do modelu (výškové kóty a hydrologická síť).

Cílem práce bylo zjistit reálně dosažitelnou přesnost DMT z nejčastěji využívaných dat, protože převážná část modelů dnes vzniká v rámci softwarových nástrojů pro GIS a jejich autoři často nemají dostatečné znalosti této problematiky a nevyhodnocují přesnost modelů. V tomto směru je důležité upozornit na to, že dosažené výsledky překračují povolená kritéria uváděných tříd přesnosti ČSN 01 3410 s výjimkou dosažených hodnot při interpolaci dat ZABAGED v modulu Topo to Raster.

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