AUTOMATING THE CREATION OF CHANNEL CROSS SECTION DATA FROM AERIAL LASER SCANNING AND HYDROLOGICAL SURVEYING FOR MODELING FLOOD EVENTS

RADEK ROUB¹⁾, TOMÁŠ HEJDUK^{1,2)}, PAVEL NOVÁK²⁾

¹⁾Czech University of Life Sciences Prague, Faculty of Environmental Sciences, Department of Water Resources and Environmental Modeling, Kamýcka 1176, 165 21 Praha 6-Suchbát, Czech Republic; Mailto: hejduk.tomas@vumop.cz

²⁾Research Institute for Soil and water Conservation, Žabovřeská 250, Praha 5, Czech Republic.

Knowing the extent of inundation areas for individual N -year flood events, the specific flood scenarios, and having an idea about the depths and velocities in the longitudinal or transverse water course profile provided by hydrodynamic models is of key importance for protecting peoples' lives and mitigating damage to property. Input data for creating the watercourse computational geometry are crucial for hydrodynamic models. Requirements for input data vary with respect to the hydrodynamic model used. One-dimensional (1D) hydrodynamic models in which the computing track is formed by cross-sectional profiles of the channel are characterized by lower requirements for input data. In two-dimensional (2D) hydrodynamic models, a digital terrain model is needed for the entire area studied. Financial requirements of the project increase with regard to the input data and the model used. The increase is mainly due to the high cost of the geodetic surveying of the stream channel. The paper aims at a verification and presentation of the suitability of using hydrological measurements in developing a schematization (geometry) of water courses based on topographic data gained from aerial laser scanning provided by the Czech Office for Surveying, Mapping and Cadastre. Taking into account the hydrological measurement during the schematization of the water course into the hydrodynamic model consists in the derivation of flow rate achieved at the time of data acquisition using the method of aerial laser scanning by means of hydrological analogy and in using the established flow rate values as a basis for deepening of the digital terrain model from aerial laser scanning data. Thus, the given principle helps to capture precisely the remaining part of the channel profile which is not reflected in the digital terrain model prepared by the method of aerial laser scanning and fully correct geometry is achieved for the hydrodynamic model.

KEY WORDS: Aerial Laser Scanning, Cross Section, Flow Rate, GIS, Hydrodynamic Model.

Radek Roub, Tomáš Hejduk, Pavel Novák: AUTOMATICKÁ TVORBA GEOMETRIE VODNÍCH TOKŮ NA ZÁKLADĚ SYNTÉZY DAT Z LETECKÉHO LASEROVÉHO SKENOVÁNÍ A HYDROLOGICKÉHO MĚŘENÍ PRO MODELOVÁNÍ POVODŇOVÝCH UDÁLOSTÍ. J. Hydrol., Hydromech., 60, 2012, 4; 25 lit., 8 obr., 5 tab.

Znalost rozsahu záplavových území pro jednotlivé N -leté povodňové události a konkrétní povodňové scénáře, včetně získané představy o hloubkách a rychlostech v podélném či příčném profilu vodního toku, které poskytují hydrodynamické modely, zaujímá výsadní postavení z pohledu ochrany životů a zmírnění škod na majetku občanů. Stěžejním faktorem pro tvorbu hydrodynamických modelů jsou vstupní data pro vytvoření výpočetní geometrie vodního toku. Požadavky na vstupní data se liší s ohledem na použitý hydrodynamický model. Jednorozměrné (1D) hydrodynamické modely se vyznačují nižšími požadavky na vstupní data, kdy výpočetní trať je tvořena příčnými profilem koryta, naproti tomu u dvourozměrných (2D) hydrodynamických modelů je nutné sestavit pro celé řešené území digitální model reliéfu. S ohledem na vstupní data a použitý model roste i finanční náročnost celého projektu. Nárůst finančních prostředků je způsoben především vysokými náklady na geodetické zaměření koryta toku. Cílem příspěvku bylo ověřit a prezentovat vhodnost využití hydrologického měření při tvorbě schematizace (geometrie) vodních toků na podkladě výškopisných dat získaných metodou leteckého laserového skenování, které zabezpečuje Český úřad zeměměřický a katastrální. Zohlednění hydrologického měření při schematizaci vodního toku do hydrodynamického modelu spočívá v odvození dosaženého průtoku v době pořizování dat metodou leteckého laserového skenování a takto stanovené průtoky lze využít jako podklad pro zahlbouení digitálního modelu

reliéfu připraveného z dat leteckého laserového skenování. Daný princip tak nahrazuje zbývající část profilu koryta, která není metodou leteckého laserového skenování v digitálním modelu reliéfu reflektována. Je tak dosaženo požadované geometrie koryta vodního toku, jehož kapacita je shodná s hodnotou průtoku v přirozeném korytě.

KLÍČOVÁ SLOVA: letecké laserové skenování, příčný profil, průtok, GIS, hydrodynamický model.

1. Introduction

Currently in the Czech Republic there is no sufficiently detailed, quality map appropriately expressing channel cross sections along the entire length of a studied water course for use in hydrodynamic models.

Elevation data are crucial for selecting hydrodynamic models for simulations (Drbal et al., 2009). From the perspective of land elevation 1-D models are less complicated, as for making calculations only the cross sections of the stream channel and the surrounding inundation zone suffice. For 2-D models in order to make calculations it is preferable to have a detailed digital terrain model (hereinafter DTM) accurately portraying the morphology of the studied area (Cobby, 2001). 1-D models allow for the schematization of longitudinal and transverse technical structures in stream channels, which is not yet possible with 2-D models. The cost of obtaining data is based on input data requirements for 1-D and 2-D models (Valentová et al., 2010).

Three basic methods for obtaining data are used in order to make hydraulic calculations using numeric models, to evaluate simulation results and for related risk analysis: geodetic transverse flow cross sections (stream channel and inundation zone), aerial laser scanning, and photogrammetry.

Geodetic stream channel and inundation zone surveying is often the most time-consuming and expensive method considering the size of the geodetic control. The maximum distance between transverse cross sections generally ranges from tens of meters to hundreds of meters based on the variability of the stream channel shape (Merwade, 2006).

Standard transverse cross section distances range from 50 m to 100 m in built-up areas to 200 m to 400 m outside of built-up areas. It is important that during surveying that the spatial variability of the water flow is obtained and that all significant changes in stream channel geometry (changes in transverse stream channel cross sections, changes in longitudinal angle, etc.) are recorded (Ramsankaran et al., 2010).

Aerial photogrammetry is used for collecting substantially accurate large- and mid-scale topographical and elevation data at a significantly lower cost than with using geodetic methods. Using aerial photogrammetry, a DTM is usually created by a basic layer of 3-D points which is supplemented by an evaluation of significant terrain edges in the form of 3-D lines (Merwade, 2008). The maximum distance between raster points should not exceed a value of 25 meters (the optimal value is from 10 to 15 m); all terrain edges and breaks must be evaluated, if their relative height is greater than 25 cm. Required accuracy is defined as having a maximum position error of 0.5 m and a standard elevation error of 0.11 m. Detailed requirements for taking measurements and creating DTMs are contained in the Guidelines for Using Photogrammetry for Defining Flood Zones (Ministry of Agriculture, no. 28181/2005-16000).

Aerial laser scanning (hereinafter ALS) of the earth's surface is one of the most modern technologies used for obtaining spatial geographic data (Dolanský, 2004). Although aerial laser scanning is a very young technology for mapping the Earth's surface and for creating DTMs or digital surface models (hereinafter DSM), it has applications in many practical disciplines. In urban planning, data can be obtained for creating 3-D city models, and in forestry for analyzing vegetation cover from the perspective of growth and development. The administrators of aboveground infrastructure use ALS data for electric transmission line models and for generating protective zones, as well as making highway, airport and railway models. This technology is also important for collecting data in hydrology. Data obtained using ALS can be applied for mapping drainage divides, for specifying the position of axes of water courses, and for identifying transverse obstacles in stream channels (Uhlířová, Zbořil, 2009).

1.1 The creation of a new hypsography of the Czech Republic using LLS

ALS generally enables a large volume of data to be obtained in a short interval of time. Considering

its relatively high level of data analysis automation for creating digital terrain and surface models, it is one of the most effective methods for obtaining spatial data (Dušánek, 2008).

Work on creating a new hypsography of the Czech Republic using the ALS method has been underway since the start of 2009. Three state agencies are in charge of it: the Czech Office for Surveying, Mapping and Cadastre (COSMC), the Ministry of Agriculture, and the Ministry of Defense (Brázdil, 2009). The Ministry of Defense is responsible for ensuring the flights of a L 410 aircraft specialized for photogrammetry, and is also responsible for analyzing data for 1/4 of the territory of the Czech Republic. The Ministry of Agriculture is responsible for renting the aerial laser scanner including related equipment, and for providing reference elevation data from measured water course cross sections. COSMC is responsible for the completion of the project and is also the main coordinator. Last, but not least, COSMC is responsible for ensuring the permanent administration of the data in the future.

The creation of a new hypsography of the Czech

Republic follows up on already existing elevation databases, restricted to the ZABAGED database (Fundamental Base of Geographic Data), created using vectorized contour lines of 1:10,000 scale basic maps (ZM 10 maps) stored as 3-D objects in DGN format. Another constantly maintained source is the ZABAGED database with perfected elevation, which is labeled with current and accurate ZM 10 contour lines, as well as terrain edges of embankments, ditches, banks, reservoirs, etc. The last ZABAGED elevation database was derived by using ZABAGED in a 10m x 10m grid. The Ministry of Defense maintains the DTM 2.5 database using 100m x 100m grids. The latest elevation database covering the entire territory of the Czech Republic is the 3rd generation DTM, which is also maintained by the Ministry of Defense of the Czech Republic. In this case it is an elevation model in the form of a triangulated irregular network (TIN) obtained using stereophotogrammetry methods. A DSM for the entire territory of the Czech Republic has yet to be created (Dušánek, 2010). The accuracy of elevation databases used until now in the Czech Republic is presented in Tab. 1.

Table 1. Elevation accuracy of databases currently used in the Czech Republic.

Data source	Mean error [m]		
	exposed terrain	ranked	forested areas
ZABAGED	0.7 – 1.5	1 – 2	2 – 5
ZABAGED updated	0.7 – 1.5	1 – 2	2 – 5
ZABAGED GRID	1.5 – 2.5	2 – 3	3 – 7
DMR 2.5 generation GRID	3 – 5	5 – 8	10 – 15
DMR 3. generation	1 – 2	1 – 2	3 – 7

After the analysis of elevation data in various time intervals, the following planned products will be created:

Fourth generation digital terrain model (DTM 4G) as a 5m X 5m grid with standard elevation error of 0.30 m in open terrain and 1 m in forested terrain (the result of preliminary automated analysis). Deadline: by the end of 2012.

Fifth generation digital terrain model (DTM 5G) in the form of triangular irregular network (TIN) with a complete standard elevation error of 0.18 m in open terrain and 0.30 m in forested terrain (final semi-automatic data analysis). Deadline: by the end of 2015.

1st generation digital surface model (DSM 1G) in the form of a triangular irregular network (TIN) with a complete standard elevation error of 0.4 m for exactly defined objects and 0.7 m for objects that are not exactly defined (forests and other vege-

tation cover elements). Deadline: by the end of 2015.

The schedule for meeting these established goals is based on application zones, which have the working titles West, Center, and East based on territorial location. At the current moment (to October 31, 2010) data sets for DTM 4G have been created for the entire Center zone, with the exception of incomplete spaces on State Maps, i.e. spaces where the interaction between data from neighboring zones has yet to be adjusted, i.e. the Center zone boundaries with the West zone and East zone, where ALS will be done in 2011 and 2012 (Dušánek, 2010).

The ALS method is based on the principle of laser beam reflections, which are interpreted as cloud point images. The advantage of this method is measurement speed, accuracy and the amount of measured data and information. A laser beam

aimed at the surface measures the distance covered towards the surface of the measured territory or object. GPS working together with inertial navigation guide the beam. An analysis of these parameters results in the calculation of the position of the given point. Output of laser scanning includes a set of 3-D coordinates of reflected points, a so-called point cloud. Classification can be made on the basis of other information about the reflected point, e.g. the intensity of reflection. A cloud point obtained in this way can be reclassified into 3(4) basic groups: terrain, vegetation, built-up areas, (errors).

The main scanning parameters for the creation of a new hypsography of the Czech Republic are: point density greater than 1.2 points/m², standard region measurement error of $\sigma < 0.03$ m, average height of flight above the terrain 1400/1200 m, absolute height of the flight in relation to relative height and hilliness of the terrain, photo strip distance 830/715 m, side lap from 35 % to 50 % (Brázdil, 2009).

T a b l e 2. Accuracy of fourth generation digital terrain model.

Category surface and land cover	Systematic error [m]	Complete medium error [m]	Maximum error [m]
Paved surfaces	-0.01	0.07	0.26
Field edges (eg mounds of roads and railways)	-0.25	0.34	0.77
Arable land	-0.01	0.13	0.66
Meadows and pastures	-0.09	0.18	0.85
Shrubs, trees and forests	-0.02	0.13	0.85

1.2 Hydrological surveying

Hydrologic surveying is the second part of the technical schematization of water courses for hydrodynamic models. The Czech Hydrometeorologic Institute (CHMI) and watershed authorities are in charge of hydrological surveying in the Czech Republic. Hydrological monitoring can be divided into two different programs, which are of course very closely related and mutually influence each other. The first program is the qualitative monitoring program, which of course is not applicable for the schematization of water courses for hydrodynamic models. The second program, which can be applied to the geometrics of hydrodynamic models, is quantitative monitoring. The quantitative monitoring of surface waters program includes the monitoring of water courses and select stationary bodies of water, but for hydrodynamic model applicability the surveying of water courses is most important.

Although small water courses make up the majority of the hydrographic network of the Czech Republic (78 % of its total length), there has been

The first results from validation and defining accuracy characteristics of ALS data were obtained from the thus far only output of DTM 4G at the start of 2011, when the Land Survey Office started distributing the DTM 4G of the Central zone of the Czech Republic. Evaluation methods for assessing the accuracy of ALS data are described in the Technical Report for the Fourth Generation Digital Model (2010), in which accuracy characteristics of this model are also published (Tab. 2).

The findings from DTM 4G accuracy validity testing indicate that the guaranteed standard elevation error of this generalized geo-terrain model (0.30 m in terrain without continuous vegetation cover and built-up areas, 1 m in terrain with dense vegetation cover) has been fulfilled, and that ALS data meet their declared accuracy, and it is also predetermined based on ALS data that other guaranteed standard errors for DTM 5G and DSM 1G will be met (Brázdil et al., 2010).

little systematic hydrological monitoring of them (Hrádek, Sobota, 1999), which is nonetheless positive taking into account possible applications of the hypothesis about ALS and hydrological survey data, as hydrological monitoring is focused mainly on significant water courses, on which data synthesis can be applied.

The scope of the water course monitoring network does not cover all surface water bodies, of which there are 1070 proposed in the Czech Republic, nor is its expansion to include all bodies of water in the near future realistic. The structure of this network however does cover significant water courses and their watersheds so that with the help of hydrological analogy (Hladný, 2002; Plate, 2002; Giannoni et al., 2003; Fowler et al., 2005) the hydrological characteristics of all places in the stream network can be determined.

Currently there are 494 operational hydrological survey stations on significant water courses on the territory of the Czech Republic. An overview of the number of water course quantitative monitoring sites is listed in Tab. 3.

Table 3. Monitoring network of surface water flowing in the Czech Republic.

River basin	Number of stations measuring water level	Number of stations with rated flow	Number of stations comprises basin
Horní and střední Labe	112	112	1
Horní Vltava	47	47	–
Berounka	40	40	2
Dolní Vltava	40	39	–
Ohře and dolní Labe	49	49	8
Odra	61	61	–
Morava	75	75	–
Dyje	70	69	–
Total	494	492	11

The continuity of hydrological surveying at a total of 494 stations provides adequate information for considering the applicability of determined flow rates for the creation of correct geometry for hydrodynamic models.

The necessity of combining data collection methods for creating hydrodynamic models significantly increases project costs. In the case of transverse stream channel cross section geodetic surveying for including stream channel information in a final DTM, the inter-cross section parts of the water course are not expressed and these sections are entered by the user directly.

In connection with the creation of a new topographic map of the Czech Republic using ALS technology and the hydrological surveying of the CHMI and watershed authorities there is an alternative possibility for synthesizing these data for the schematization of water courses for hydrodynamic models, wherein an original combination of information about the established flow rate at the time of elevation surveying using ALS with the actual ALS data is used.

2. Materials

The possibility of synthesizing hydrological survey data and data from the new hypsography of the Czech Republic was verified on a section of the Orlice water course (Divoká Orlice, Tichá Orlice), to the west of Hradec Králové in Eastern Bohemia (Fig. 1), which is delimited by the municipalities of Třebechovice pod Orebem – Borohrádek – Čestice.

The study area was selected primarily for the large number of monitoring stations conducting hydrological surveying, and for subsequent flow rate evaluation and ALS data analysis, which has already undergone a manual check including the derived terrain model (GROUND data) and data from the geodetic surveying of water course cross

sections. Hydrological stations are located either directly on the monitored water courses in marginal zones of the studied territory where it is possible to derive the flow rate. To verify flow rates established in this way, there was the possibility of using hydrological monitoring stations located on the tributaries of studied water courses. Hydraulic and hydrological characteristics were another important reason for selecting the locality.

The data from the new topographic mapping were critical, which were accessed in the S-JTSK coordinate reference system and in the Baltic vertical datum system in ASCII text format with X, Y, H values in the form of classified cloud point with a density of 1.2 points/m², and in the following classes: G – terrain, B – buildings, V – vegetation, H – height barriers (elevation points greater than 46 m above the surface), E – errors, F – artificially generated 5 m x 5 m grids (in places where there were no data), M – bridges. A standard coordinate elevation error of $mH = 0.18$ m was assumed for the data.

Hydrological data for the modeled scenarios were obtained from the Czech Hydrometeorology Institute's water gauge records. In order to compare the results, established N -year flow rates were used for three flood episodes Q_{20} , Q_{50} , and Q_{100} . Data about N -year flow rates were obtained from four hydrological surveying stations located directly on the studied water courses. Hydrological data about maximum flow rates during ALS data acquisition were obtained for four hydrological surveying stations located directly on the studied water courses and were obtained from the water management control system of the Povodí Labe s.p. watershed authority, headquartered in Hradec Králové. For more exact flow rates obtained during ALS, stations located on tributaries in the study area were also used.

Fig. 1. Experimental area.

Geodetically surveyed stream channel cross sections of the Orlice, provided by the Labe watershed authority, were used for objective comparison. Distance intervals between measured stream channel cross sections ranged from 80 to 250 m, which provided ample information for further operation. Data were taken in the form of discrete elevation points measured in the S-JTSK coordinate reference system and in the Baltic vertical datum system, in ASCII text format with X, Y, and H values. The data also contained information about the type of surveyed object (slope edge, protection wall, etc.).

In relation to the new topographic mapping of the Czech Republic using ALS technology and with respect to the continuous monitoring of the Czech Hydrometeorological Institute and watershed authorities, possibilities for applying the established flow rate during the acquisition of elevation data using ALS were monitored as an input factor in the creation of hydrodynamic models. In connection to accuracy and the principle of obtaining ALS data the applicability of using hydrological measurements for creating water course schematization was verified. Based on the synthesis of elevation data obtaining using ALS and hydrological surveying, the idea of deepening the transverse and longitudinal cross sections of the stream channel by the flow profile (determined by flow rate during ALS) was tested (deepening the DTM only using ALS data).

Applicability of the mentioned data synthesis was verified using a 1-D hydrodynamic model, which suitably predefined the character of study areas indicating appropriate conditions for the application of 1-D models (Horritt, Bates, 2002). 1-D models allow for the schematization of longitudinal and transverse technical structures in stream channels, which is not yet possible with 2-D models.

The freely available HEC-RAS model was used, which allows for one-dimensional calculations of steady and non-steady, non-uniform flow, sediment transport (movable bed) or the modeling of temperature changes in flowing water. In order to assess whether it is possible to use hydrological surveying for the creation of flow geometry, a steady flow calculation was used. The calculation of steady flow is based on a calculation of non-uniform water flow in the stream channel in sections. The program can divide the cross section into the actual stream channel (i.e. the effective area of flow), and the left and right inundation zones. Determining water surface profiles with HEC-RAS is based on a one-dimensional method using Bernoulli's principle. Energy losses are calculated by friction loss using Manning's equation, while local losses are expressed with contraction and expansion coefficients. Areas that are more hydraulically complex such as overfalls, confluences, bifurcations, bridges and culverts are dealt with using modified equations of movement.

For working with geometric data and for final visualization the HEC-GeoRAS extension was used, which is a set of tools for working with geospatial data in ArcGIS with the help of a graphic user interface (GUI). The interface makes working with geometric data in the form of a calculated track schematization possible as well as exporting this data to the HEC-RAS environment, where the actual simulation is made, and output can then be imported back into ArcGIS, where they can serve as input for related analyses such as mapping flood risks, etc.

For assessing applicability of the synthesis of ALS data and hydrological survey data, an integrated, scalable and open GIS in the form of ArcGIS from the company ESRI was used. It has powerful editing, analysis, modeling and data administration tools, which makes it the most comprehensive GIS software on the world market today (Čejp, Duchan, 2008). Two extensions were also used: *Spatial Analyst* and *3D Analyst*. The first of these extensions offers a wide range of tools for spatial modeling and analysis with which raster data can be created, displayed, queried and analyzed. With ArcGIS *Spatial Analyst* combined vector-raster analyses can also be done. With the use of the ArcGIS *Spatial Analyst* extension it is possible to obtain information from data, define spatial relationships, search out suitable areas, and calculate costs for moving from one location to another. *3D Analyst* gives users the possibility to effectively visualize

and analyze representative data. Using ArcGIS *3D Analyst*, you can view large sets of data in three dimensions from multiple viewpoints, query a surface, and create a realistic perspective image that drapes raster and vector data over a surface. *3D Analyst* also offers advanced GIS tools for three-dimensional modeling, and terrain visibility and modeling.

3. Methods

The methodology for ALS and hydrological survey data has already been published in other works (Roub et al. 2012, Novák et al. 2011). In the first publication output from assessing the applicability of ALS data for analyzing and mapping flood risks was presented, the conclusion of which was that based on comparative analyses of data from geodetic measuring and ALS data, as well as from the findings of 1D hydrodynamic models, that ALS data meet their declared accuracy and that they can serve as a suitable data source for determining the elevation of inundation zones of water courses for the creation of hydrodynamic models. Reflected local depth depressions in the form of roadside ditches are interesting as are inflow areas in the form of road crossings from the perspective of potential anti-flood protection in built-up areas.

The second publication dealt with possibilities for using established flow rates at the time of elevation data acquisition through ALS for lowering flow rate values in simulations. The partial replacement of costly geodetic surveying was also considered with available data from flow rate hydrological surveying that accurately resemble transverse channel cross sections along the entire longitudinal profile, which, taking into consideration limitations on measuring transverse stream channel cross sections, does not provide relevant information for inter-cross section areas. For assessment, scenarios were modeled with both simulated flow rate lowered to the measured value of flow rate at the time data was acquired with ALS, i.e. on the basis of the DTM generated only from ALS data, as well as scenarios without lowering the simulated flow rate, i.e. on the basis of a DTM with additional water course channel data (ALS data + geodetic measurements). From the findings it can be stated that using hydrological surveying for lowering model scenarios in hydrodynamic models is possible, however it is necessary to define input conditions in the transition zone in order to accurately determine perpendicular speed differences

along every step of the calculated track, and this must be expressed in hydrodynamic models. The most suitable and at the same time simplest variant was when the channel roughness was set appropriately using the roughness coefficient. Using an appropriate setting led to a change in increased speed in the transverse channel cross section in the transition zone.

During the geometric surveying of transverse cross sections and the interpolation of inter-cross section areas, i.e. during the drawing of bank edges and stream channel morphology, there are increases or even decreases in channel cross section capacity as a result of surveyor subjectivity.

The process of automating the creation of transverse cross sections will reduce this. This technical approach describes transverse stream channel cross sections with the required accuracy along the length of the entire water course. It is essentially based on the use of data from hydrological surveying for drawing transverse stream channel cross sections in areas where ALS data are not reflected.

The synthesis of ALS and hydrological survey data uses a basic characteristic of ALS data, wherein the laser beam is not reflected after striking the water's surface, but instead is absorbed by the water (Fig. 2). On the basis of this during the analysis of ALS data there is a loss of information in areas where there is a continuous water surface. The basic product of ALS, cloud points, thus after the transformation of measured values into elevation figures, do not depict the entire transverse cross section of the stream channel, but only the part of it where the beams reflected from. The capacity of a missing part of the stream channel may be a significant flow area, and may during flood events carry a significant volume of the flood wave, and therefore should be filled in using data about flow rate from the time of ALS data acquisition. Fig. 3 shows how the transverse channel cross section data from ALS data were inserted into the DTM, without which this part of the stream channel would not be reflected.

Two approaches for analysis were used; in the first case data was analyzed directly in GIS. The second approach involves the use of specialized software for the schematization of water flow geometry.

As a result of this similar method being used, GIS is used for initial data analysis from hydrological survey stations. It is necessary to obtain data about flow rates during ALS data acquisition from relevant stations, as they will be used for creating

the actual transverse channel cross section in the DTM using ALS data. In the second step of the technical analysis done in GIS (ARCGIS 10) a polygon layer is created over the water course in areas where there are no data from ALS using the *Spatial Analyst* and *3D Analyst* extensions. Based on the DTM created only from ALS data the water course surface slope is obtained, which is then used as an input parameter in the transformation formula for deepening the stream channel – the Chézy formula (Eq. 1) is considered in combination with the continuity equation (Eq. 2). For describing the remaining parameter – the water depth by which the DTM must be deepened using ALS data – predefined stream channel profiles can be selected – trapezoidal – parabolic – rectangular.

$$v = C \sqrt{RI}, \quad (1)$$

where v – mean velocity [m s^{-1}], C – Chézy coefficient [$\text{m}^{0.5} \text{s}^{-1}$], I – longitudinal surface slope [–], R – hydraulic radius [m].

$$Q = vS = CS\sqrt{RI}, \quad (2)$$

where Q – flow rate [$\text{m}^3 \text{s}^{-1}$], S – flow area [m^2].

On the basis of flow rate data at the time of ALS, water course surface data (generated from the DTM created from ALS data), data about channel surface width (polygon layer generated on the basis of data not recorded during ALS, i.e. where the beam was absorbed by the water surface) and flow rate data a predetermined transverse cross section shape is selected and the required depth is calculated, and subsequently the stream channel is accordingly deepened in the DTM using ALS data, and a synthetic map is created which depicts correct water

course transverse cross sections and inter-cross section areas.

The generated width on surface B, the longitudinal surface slope I , and the flow rate Q obtained from hydrological surveying on the water course were used in the Chézy formula and the continuity equation to calculate the shape of the transverse cross section. These three values define the creation of transverse cross sections. Another characteristic, which can be selected by user (derived from field research) is Manning's roughness coefficient n . The quantification of uncertainty during the selection of Manning's roughness coefficient and its impact on the reliability of determining the stream channel was the subject matter of a sensitivity analysis that was conducted. Establishing an $-m$ value determining the angle of the cross section slope (for trapezoidal cross sections) is based on the course of the surveyed cross section in the immediate vicinity of the water surface. A part of the transverse stream channel water course is recorded using ALS, and this part is then used as a base for determining the m -value.

It includes variants for creating trapezoidal, parabolic, and rectangular shaped transverse cross sections. All variants follow the same procedure, involving gradually increasing water depth y and the subsequent flow rate calculation Q for each selected water depth y until the required flow rate Q value is reached. Once this point has been reached the coordinates of the transverse cross section are generated for subsequently adding a polygon layer in places where ALS beams were absorbed by the surface.

Fig. 2. Sample data ALS.

Trapezoidal cross section **Rectangular cross section** **Parabolic cross-section**

Fig. 3. Inserted into the channel cross-section of the DMR data ALS.

4. Results

Two model scenarios were used for evaluating the relevance of hydrological survey data used for creating a DTM for the schematization of water course geometry in hydrodynamic models.

A comparison of transverse cross sections generated from the final DTM after deepening based on flow rate during ALS data acquisition with geodetically surveyed transverse cross sections was first done. During this analysis in places where trans-

verse cross sections were geodetically surveyed new transverse cross sections from the DTM were drawn in created from the synthesis of ALS data with hydrological survey data, which were then compared with the geodetically surveyed transverse cross sections (Fig. 4).

The level of correspondence (Fig. 5) is in such cases quite satisfactory. Despite the fact that the depicted cross sections are not completely identical, in this case there is a flow cross section difference of max. 4.1 m^2 , which equates to water flow rate of

$6.8 \text{ m}^3 \text{ s}^{-1}$ under these conditions. For the determined flow rate Q_{100} of $516 \text{ m}^3 \text{ s}^{-1}$ in Týniště nad Orlicí this is 1.31 % of the maximum flow rate of a 100-year flood. Findings from each transverse cross

section (from geodetic surveying, and from the DTM cross sections created based on the synthesis of ALS data and hydrological survey data) can be found in Tab. 4.

Fig. 4. Scenario 1. variants.

Fig. 5. Results of the first scenario variaty.

T a b l e 4. The achieved results geodetically focused cross sections.

Indication	Reference - geodetic focused (Source: PLA)		DMR data from LLS and hydrological measurements	
	flow profile [m^2]	flow profile [%]	flow profile [m^2]	flow profile [%]
A1	173	100	169	97.69
A2	202	100	199	98.51
A3	182	100	186	102.20

For the second model scenario additional geodetic surveys of transverse cross sections were used, which were located in between the geodetic surveys of transverse cross sections available from the Povodí Labe s.p. watershed authority. The goal of this analysis was to evaluate the accuracy of the fit between the deepened DTM with the geodetically surveyed cross sections (model scenario 1), where the main intent was to observe transverse cross sections obtained from a DTM created with the standard method of interpolating the inter-cross section areas from ALS data (inundation zones) and the geodetically surveyed transverse cross sections provided by the Povodí Labe s.p. watershed authority (stream channel) with subsequent transverse cross section surveying (Fig. 6).

The results indicate high fluctuation when comparing geodetically surveyed transverse cross sections with the cross sections obtained from the DTM, where the stream channel cross section was edited manually (Fig. 7). This results in excessive increases and decreases in the capacity of stream channel cross sections in comparison with the cross sections obtained via geodetic surveying (for the analysis of cross sections subsequently surveyed). The extremes of the fluctuations grow with the distance from geodetically surveyed cross sections, which were used for this analysis as a reference (meaning the geodetically surveyed cross sections of the Povodí Labe s.p. watershed authority), wherein at the halfway point between neighboring cross sections differences are the highest, and sub-

sequently decrease as the next geodetically surveyed (reference) cross section is approached, as indicated in Fig. 8. The results of the comparison between subsequent geodetic cross section surveying and cross sections from the DTM created on the basis of the synthesis of ALS data with hydrological surveying indicate that the accuracy of the cross sections from the DTM are in the same range as in the first model scenario. The values obtained from transverse cross sections (from subsequent cross section geodetic surveying vs. cross sections obtained from DTM based on the synthesis of ALS data with hydrological survey data vs. cross sections from the manually edited DTM) can be found in Tab. 5.

In connection with the comparative analysis and with the help of the HEC – GeoRAS extension a geometric schematization of the entire study section of the water course was created, which was the base for the HEC – RAS hydrodynamic model. The ArcGIS export package was subsequently imported into the HEC – RAS program for the purpose of making calculations. Visualization of the results, the generation of depth rasters and the determination of flood zones was also done using ArcGIS software with the help of HEC – GeoRAS tools. The results were compared with surface levels records from actual flood events that occurred in the past on the Orlice. This comparison was approached objectively outside of the framework of the model flood episodes Q_{20} , Q_{50} , and Q_{100} .

Fig. 6. Scenario 2. variants.

Fig. 7. Results of the second scenario variaty.

Table 5. The achieved results with additional geodetically focused cross sections.

Indication	Reference - geodetic focused (Source: additionally targeted for analysis)		DMR data from LLS and hydro- logical measurements		DMR data from LLS and geodesic interpolation of the measured profiles from PLA	
	flow profile [m ²]	flow profile [%]	flow profile [m ²]	flow profile [%]	flow profile [m ²]	flow profile [%]
B1	180	100	182	101.11	170	94.44
B2	178	100	181	101.69	191	107.30
B3	183	100	180	98.36	189	103.28
B4	186	100	184	98.92	178	95.70
B5	191	100	193	101.05	198	103.66

For modeling specific flow rates (Q_k) from actual flood events, the relevance of the results to reality was monitored, or if the accuracy of the synthesis of ALS data with hydrological survey was met. The findings indicate the validity of the synthesis of ALS data with hydrological survey data, where established inundation lines correspond very well with preserved records (flood records, photography, etc.) and high water marks.

Fig. 8. Achieved by variation in profiles B1 to B5.

For the simulation of N -year flood episodes Q_{20} , Q_{50} , and Q_{100} results were compared with the results of the model of water course geometry made based on the manually compiled DTM. The goal of this comparison was to describe the concurrence between resulting rasters from the DTM made based on mentioned sources of data. For evaluating concurrence a function was used for subtracting both rasters, from which a differential raster was obtained, documenting the differences in results. The differential raster indicates mainly local variability, which can be attributed to various methods of working with data. However, further conclusions cannot be specified from the results, because claims about the accuracy or inaccuracy of the DTM are groundless as there is no reference data.

The comprehensive comparisons include a comparison of determined flood zones. During analysis not only were inundation lines from the DTM used (DTM made with the manual editing of stream channel cross sections vs. DTM made on the basis of the synthesis of ALS data with hydrological sur-

vey data), but also official inundation lines of the PLA. Results indicate the variability of inundation lines, which is especially marked outside of built-up areas, whereas in built-up areas they concur relatively well with each other. Inundation lines are very similar, especially inundation lines that are to serve as background data for ALS of the inundation area. In comparison with the inundation lines of the PLA, where photogrammetry is used, there is less concurrence, which can surely be attributed to differing background data in the inundation zone, and not just as a result of the manual modification of the stream channel cross section.

5. Discussion

The synthesis of hydrological survey data with ALS data using the described technical method is characterized by the fact that it replaces the shape of the natural stream channel cross section and the surrounding inundation zone along the length of the entire studied water course. Currently, one of the three above described cross sections can be used for these replacements. It is assumed that further research will expand the selected cross sections to include other shapes which will make them closer to natural conditions.

The results from the 1D hydrodynamic model and from the comparative analysis of geodetic survey data with ALS data indicate that these findings may be useful in practice.

The results of comparison with subsequent transverse cross section geodetic surveying are important as they indicate favorable concurrence as opposed to the variant where the stream channel cross section has been edited by the user. This only serves to confirm the hypothesis about the impossibility of accurately describing inter-cross section areas of the stream channel, delimited by two geodetically surveyed transverse cross sections, where when depicting the bank edges and the morphology of the stream channel the stream channel cross section capacity is either increased or decreased as a result of the subjectivity of the analyst.

The results have a positive impact on cost reduction, which is unarguably connected to the creation of a hypsography using geodetic surveying for compiling a hydrodynamic model. As costly geodetic surveying can be partially replaced by the synthesis of ALS data with hydrological survey data for the creation of hydrodynamic models, the necessity to conduct geodetic surveying is limited,

which is reflected in costs for compiling the hydrodynamic model.

During the analysis the question of whether small water courses should be deepened or not was addressed. The use of ALS data offers an answer, as it provides a quality description of the elevation of the area, not only for mapping flood risks on large water courses, but it can also be used for determining the flood zones of small water courses with flow in small depths, where it is not necessary to combine with geodetic surveying or combine ALS data with data from hydrological survey data. In such cases the laser beam is reflected from the bottom of the stream channel, or during the creation of a DTM the level of the bank compared to the bottom represents such a low value that it is negligible for the purpose of modeling (Novák et al., 2011). However one question remains and that is how to appropriately select and include water courses in a category where it is necessary to deepen the channel or in a category where using ALS data is enough.

Data from ALS offer special elevation data for the Czech Republic (Roub et al., 2011) which can reflect local depth depressions in the form of roadside ditches or inflow areas in the form of road crossings from the perspective of potential anti-flood protection in built-up areas. The generated depth raster with a selected 30 cm grid can describe the morphology of the terrain of the study area quite well, which offers up an above average idea of the area of the flood zone according to various flood scenarios. All of these things are positive benefits for the analysis and mapping of flood risks as crucial background information for preventive flood protection.

However, it was shown that a limiting factor during calculation was the volume capacity of data reaching up to several GB (depending upon the layer of reclassification), which had a negative impact on data analysis. For creating risk analyses of complex river systems and assuming data volumes of several hundred GB, this fact will have to be adjusted to the technical and IT capacity. There is also the consideration about how to appropriately reduce TIN use so that data volume is not reduced at the expense of recorded terrain morphology, thus leading to a loss in accuracy and certainty in flood models.

The quantitative hydrological monitoring network, with hydrological surveying stations mainly on significant water courses, offers the potential to be used for the creation of a final DTM. The com-

plexity of using hydrological data however in this case causes problems with covering water courses for which hydrological surveys are not available, yet are borderline cases of water courses that need to be deepened or not.

The described procedure, once in the process of being generalized, will also require the quantification of the uncertainty of input variables in order to determine their influence on the uncertainty of derived stream channel depth. This uncertainty primarily deals with determining the slope of the surface, the width of stream channel at the surface, the shape of the stream channel, maximum flow rate during laser scanning, and determining the roughness of the stream channel. Partial sensitivity analyses were conducted in order to quantify the uncertainty of each input variable and their impact on the reliability of determining the sought after stream channel depth. The results of the sensitivity analyses for the described input variables indicate that the described method is sufficiently subtle for application during flood scenarios. Conducting detailed sensitivity analysis for all input variables should be the subject of further study. In this case geodetic data was used to verify the model.

6. Conclusion

This method of creating hydrodynamic model geometry meets the required values for validity as a result of its combination of information on the value of determined flow rate at the time of elevation data acquisition using ALS with ALS data. The required accuracy was achieved using GIS tools, and could not have been achieved using other existing methods or materials. If the established elevation error of 0.18 m is adhered to using ALS, then this procedure will be significantly sped up and the costs of predicting the extent of the flood zones will be reduced. In the watersheds of important water courses whose cross sections have been surveyed this method will undoubtedly be advantageous. The accuracy of the described manner of creating the geometry for hydrodynamic models is dependent on the established elevation error of 0.18 m. With the development of technology for scanning the surface of the Earth, this margin of error will subsequently drop. In addition the accuracy of this manner of geometry creation will also be increased along with the possibility of wider practical use.

The acquisition of partial data is relatively clear and accurate, which predetermines reaching appropriate results for final water course geometry for

the needs of hydrodynamic modeling. In order to generalize this approach however, in the future it will be necessary to conduct the above mentioned detailed sensitivity analysis of the quantification of the uncertainties of input variables.

Another positive are the findings that data from the new elevation mapping of the entire territory of the Czech Republic using ALS provide requested background data for flood analysis, either in combination with water course stream channel geodetic surveying (Novák, et al. 2011), with the use of hydrological surveying for reducing flow rate in model scenarios (Roub et al. 2012), or with the possibility of additional water course channel deepening in the DTM using ALS data in combination with hydrological surveying data. At the same time another definite benefit is that newly acquired elevation data has found an application for being used for dealing with water management issues, and in other fields where knowledge about the vertical division of the land is decisive.

Hydrological data leading to the deepening of the DTM from ALS data provide the ability to create a hydrodynamic model for which all hydraulic conditions will be met and output from which will be able to be used for creating flood danger and flood risk maps or for related risk analysis without the necessity of further simplifying the model, as is necessary for example for modeling flood scenarios with lowered flow rate.

The newly obtained hypsography data will be used as a complex background for solving problems requiring knowledge about vertical segmentation of the landscape in water management and many other fields.

The method described for the automatic creation of water course geometry using ALS in combination with information about current flow rates in each water course is slightly applicable outside of the Czech Republic in relation to the use of laser scanning in the world. Large scanned areas, for example in Bavaria, France, etc. where scanning has been conducted using much greater point density per m² than in the entire Czech Republic, present a base for the claim that the synthesis method could become important in science in the world.

Further research will be focused on determining marginal conditions for which it is still necessary to deepen the DTM or to use a DTM created only from ALS data. Possibilities for greater variability in predetermining stream channel cross sections (widening and multiple cross sections, etc.) will also be studied. For wider application in the future

it will also be necessary to take into consideration the identification of transverse objects (weirs, locks, etc.). The identification of transverse objects in water courses using ALS has already been studied by the authors, and it seems that the localization of objects should be problem-free, which is supported by other authors (Uhlířová, Zbořil, 2009). Nonetheless for creating correct water course geometry for water courses containing objects, it is necessary to suitably define conditions for their inclusion.

Acknowledgements. This article was written using data from aerial laser scanning, which was provided by the Land Survey Office's office in Pardubice and from geodetic survey data from the Povodí Labe, s.p. water authority in Hradec Králové.

This contribution was supported by the Research Programmes of the Ministry of Agriculture of the Czech Republic, No. MZE 0002704902 and by the Project No. TA02020139 of the Technology Agency of the Czech Republic.

REFERENCES

- ARCDATA PRAHA, 2001: Seznamte se s ARCGIS, uživatelská příručka.
- BRÁZDIL K., 2009: Projekt tvorby nového výškopisu území České republiky. Geodetický a kartografický obzor, 55, (97), č. 7, 145–151.
- BRÁZDIL a kol.: Technická zpráva k digitálnímu modelu reliéfu 4. Generace. Zeměměřický úřad, Vojenský geografický a hydrometeorologický úřad, říjen 2010.
- DOLANSKÝ T., 2004: Lidary a letecké laserové skenování. Acta Universitatis Purkynianae, 99, Studia geoinformatica, Univerzita J. E. Purkyně v Ústí nad Labem, ISBN 80-7044-575-0.
- COBBY D. M., MASON D. C., DAVENPORT I. J., 2001: Image processing of airborne scanning laser altimetry data for improved river flood modeling. ISPRS J. Photogrammetry & Remote Sens., 56, 121–138.
- ČEJP J., DUCHAN D., 2008: Využití ArcGIS 9.x pro řešení úloh 2D proudění vody o malé hloubce. Juniorstav, Vodní hospodářství a vodní stavby.
- DRBAL K. a kol., 2009: Metodika tvorby map povodňového nebezpečí a povodňových rizik. Ministerstvo životního prostředí, 87 s.
- DUŠÁNEK P., 2008: Tvorba digitálních modelů z dat leteckého laserového skenování a jeho využití pro aktualizaci výškopisu ZABAGED. Diplomová práce – Přírodovědecká fakulta Univerzity Karlovy v Praze.
- DUŠÁNEK P., 2010: Projekt tvorby nového výškopisu území České republiky. In workshop září 2010.
- FOWLER H. J., EKSTRÖM M., KILSBY C. G., JONES P. D., 2005: New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. Assessment of control climate. J. Hydrol., 300, 212–233.
- GIANNONI F., SMITH J.A., ZHANG YU and ROTH G., 2003: Hydrologic modeling of extreme floods using radar rainfall estimates. Advances in Wat. Resour., 26, 2, pp. 195–203.
- HAVLÍK A., SALAJ M., SATRAPA L., FOŠUMPAUR P., HORSKÝ M., 2004: Metodika mapování povodňových rizik s pomocí geografických informačních systémů. ISBN 80-01-02910-7.
- HLADNÝ J., 2002: Meteorologické a hydrologické syndromy povodňové situace v srpnu 2002. In Workshop Extrémní hydrologické jevy v povodích. Praha, ČVUT, ČVHS, 12. 11. 2002, s. 13–26. ISBN 80-01-02686-8.
- HORRITT M. S., BATES P. D., 2002: Evaluation of 1D and 2D numerical models for predicting river flood inundation. J. Hydrol., 268, 87–99.
- HRÁDEK F., SOBOTA J., 1999: Prognózy maximálních průtoků v nepozorovaných profilech povodí drobných vodních toků. In Workshop Extrémní hydrologické jevy v povodích. Praha, ČVUT, ČVHS, 25. 10. 1999, s. 82–85. ISBN 80-01-02072-X.
- MERWADE V. M., COOK A., COONROD J., 2008: GIS techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping. Environmental Modelling & Software, 23, 1300–1311.
- MERWADE V. M., MAIDMEND. R., GOFF J. A., 2006: Anisotropic considerations while interpolating river channel bathymetry. J. Hydrol., 331, 731–741.
- NOVÁK P., ROUB R., HEJDUK T., 2011: Využití hydrologického měření při tvorbě hydrodynamických modelů z dat leteckého laserového skenování. Vod. Hospodář., 61, 8, 297–302.
- PLATE E. J., 2002: Flood risk and flood management. J. Hydrol., 267, pp. 2–11.
- Program kvantitativního monitoringu povrchových vod v ČR, Úsek hydrologie, Český hydrometeorologický ústav, Praha, 2007.
- RAMSANKARAN R., MAERKER CH., MALCHEREK A., 2010: Numerical modelling of hydrodynamics and sediment transport processes during storm events in a non-perennial river. J. Hydrol. Hydromech., 58, 1, 36–48.
- ROUB R., HEJDUK T., NOVÁK P., 2012: Využití dat z tvorby nového výškopisu území České republiky metodou leteckého laserového skenování při analýze a mapování povodňových rizik. Geodetický a kartografický obzor, 58/100, 1.
- UHLÍŘOVÁ K., ZBOŘIL A., 2009: Možnosti využití Laserového snímání povrchu pro vodohospodářské účely. Vod. Hospodář., 59, 12, 11–15, ISSN 1211-0760.
- VALENTOVÁ J., VALENTA P., WEYSKRABOVÁ L., 2010: Assessing the retention capacity of a floodplain using a 2D numerical model. J. Hydrol. Hydromech., 58, 4, 221–232.
- Metodický pokyn (28181/2005-16000) k zadávání fotogrammetrických činností pro potřeby vymezování záplavových území v souvislosti s aplikací ustanovení § 66 odst. 1 zákona č. 254/2001 Sb., o vodách a o změně některých zákonů (vodní zákon), ve znění pozdějších předpisů, a vyhlášky č. 236/2002 Sb., o způsobu a rozsahu zpracování návrhu a stanovování záplavových území.

Received November 3, 2011

Accepted March 13, 2012